Simulation of electron cloud effects in Project X Main Injector

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SciDAC-3 ComPASS collaboration meeting – September 28, 2012

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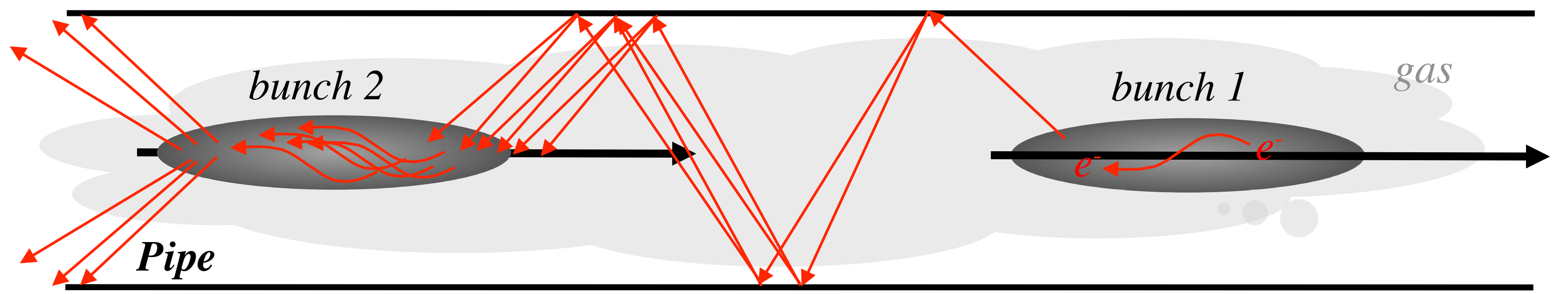
Outline

- Electron cloud effects & codes
- Recent achievements under SciDAC-II
- Plans for SciDAC-III

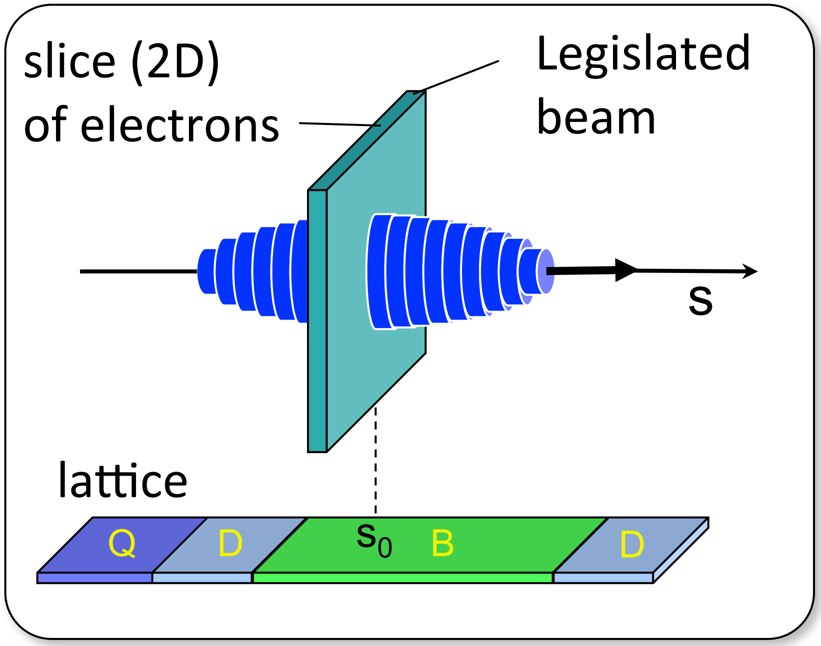
Electron-cloud driven instability observed in high-intensity rings

In FNAL main injector (MI), instability is seeded by residual gas



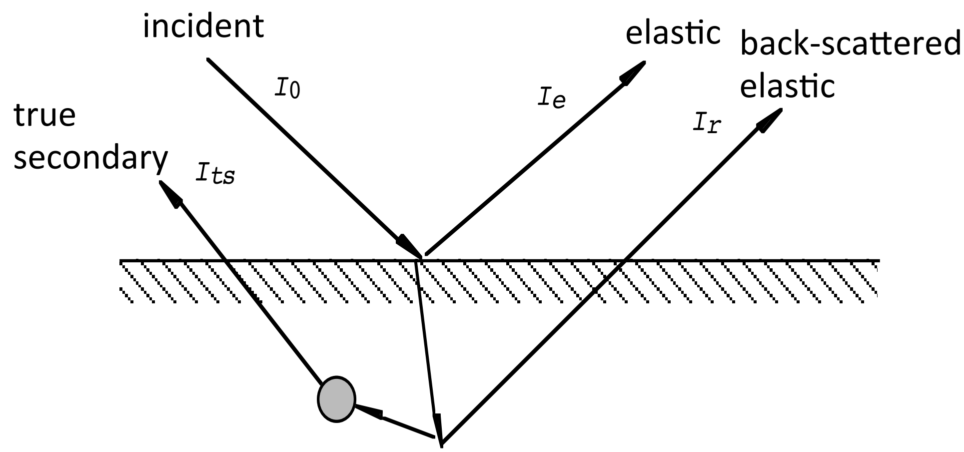
- residual gas are ionized by particle bunches,
- electrons get accelerated by bunches and eventually reach walls,
- secondary emission of electrons at walls multiply # of electrons,
- electron density rises exponentially until saturation is reached,
- Interaction of electron clouds may be resonant and degrade bunches quality.

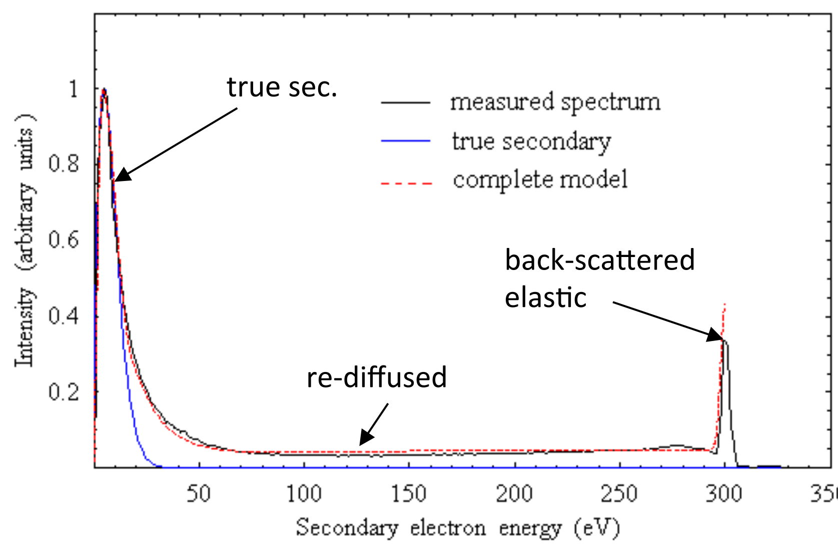
2D-PIC code Posinst used for modeling of electron cloud buildup



- Monte-Carlo generation of electrons with energy and angular dependence,
- phenomenological model: adjustable parameters fixed by fitting to data,
- also used successfully in space industry for study of satellites electrical charging.

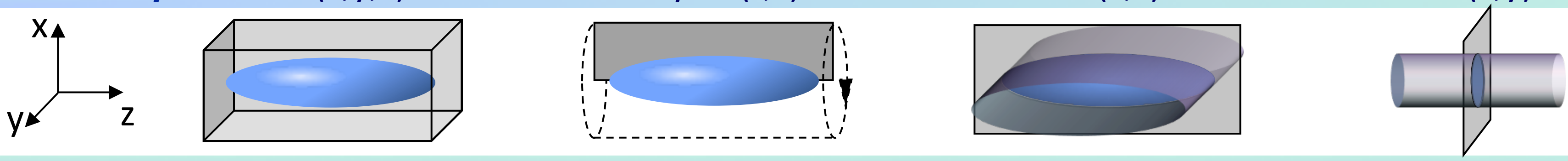
Posinst has advanced secondary electrons model (also distributed in Txphysics)





Warp is used for studying the effect of e- clouds on the beam

- **Geometry:** 3-D (x,y,z) axisym. (r,z) 2-D (x,z) 2-D (x,y)

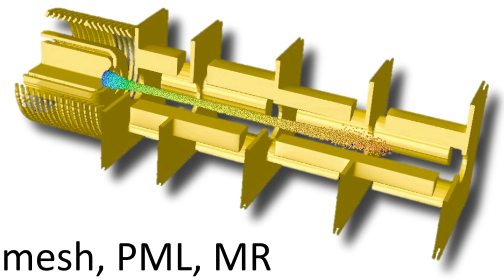


- **Reference frame:** **lab** **moving-window** **Lorentz boosted**

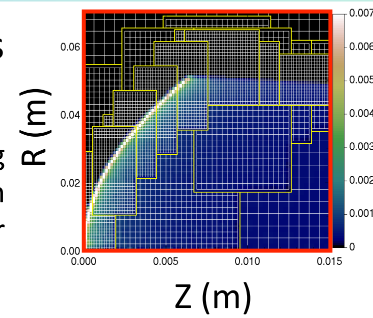
	lab	moving-window	Lorentz boosted
	z	z-vt	$\gamma(z\text{-}vt)$; $\gamma(t\text{-}vz/c^2)$

- **Field solvers**
  - electrostatic/magnetostatic - FFT, multigrid; AMR; implicit; cut-cell boundaries

Versatile conductor generator accommodates complicated structures



Automatic meshing around ion beam source emitter

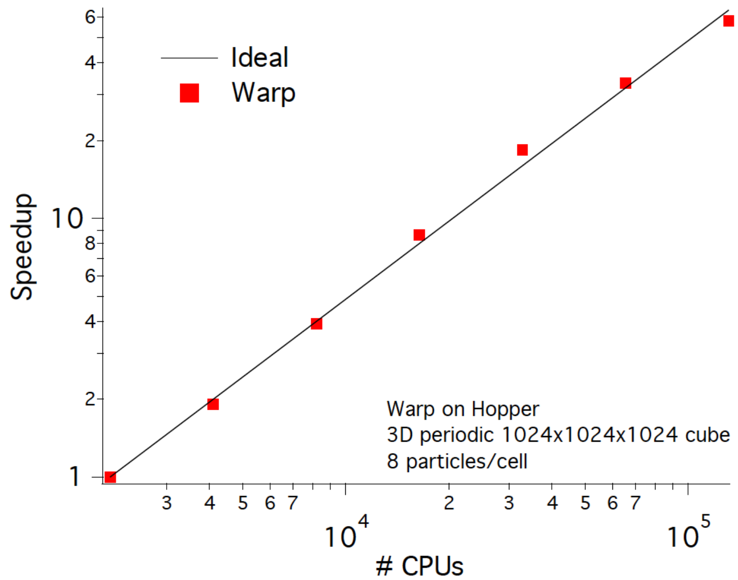


  - Fully electromagnetic - Yee mesh, PML, MR
- **Accelerator lattice:** general; non-paraxial; can read MAD files
  - solenoids, dipoles, quads, sextupoles, linear maps, arbitrary fields, acceleration.
- **Particle emission & collisions**
  - particle emission: space charge limited, thermionic, hybrid, arbitrary,
  - secondary e- emission (Posinst), ion-impact electron emission (Txphysics) & gas emission,
  - Monte Carlo collisions: ionization, capture, charge exchange.

Warp is parallel, combining modern and efficient programming languages

- **Parallellization:** MPI (1, 2 and 3D domain decomposition)

Parallel strong scaling of Warp 3D PIC-EM solver on Franklin supercomputer (NERSC)



- **Python and FORTRAN*:** "steerable," input decks are programs

```
From warp import *
…
nx = ny = nz = 32
dt = 0.5*dz/vbeam
…
initialize()
step(zmax/(dt*vbeam))
…
```

- From warp import * ← Imports Warp modules and routines in memory
- nx = ny = nz = 32 ← Sets # of grid cells
- dt = 0.5*dz/vbeam ← Sets time step
- initialize() ← Initializes internal FORTRAN arrays
- step(zmax/(dt*vbeam)) ← Pushes particles for N time steps with FORTRAN routines

*http://hifweb.lbl.gov/Forthon (wrapper supports FORTRAN90 derived types) – dpgrote@lbl.gov

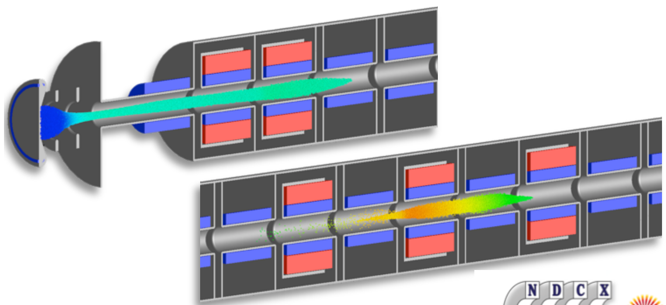
Warp's versatile programmable framework allows great adaptability

Standard PIC

Moving window

Example:

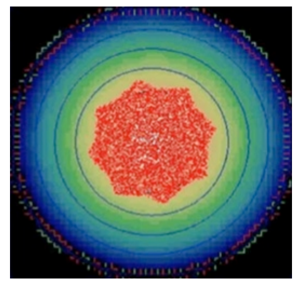
Beam generation & transport



Laboratory frame

Example:

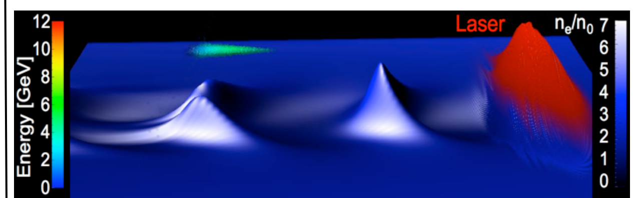
Alpha anti-H trap



Lorentz Boosted frame

Example:

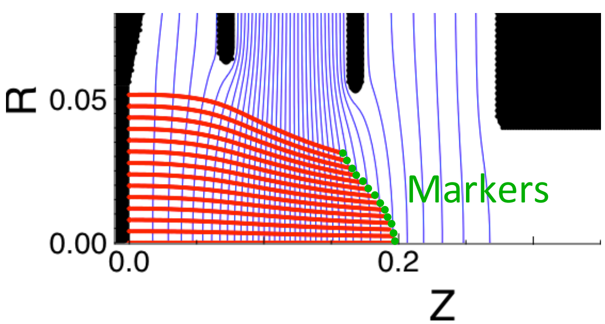
Laser plasma acceleration



Non-standard PIC

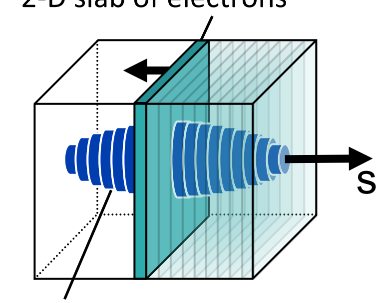
Steady flow

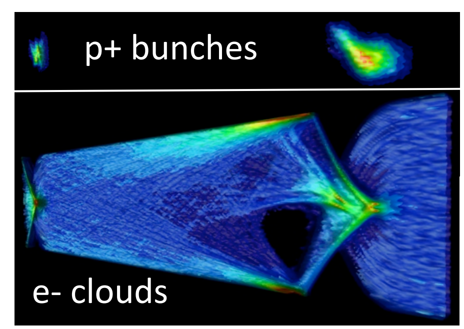
Example: Injector design



Quasi-static

Example: electron cloud studies





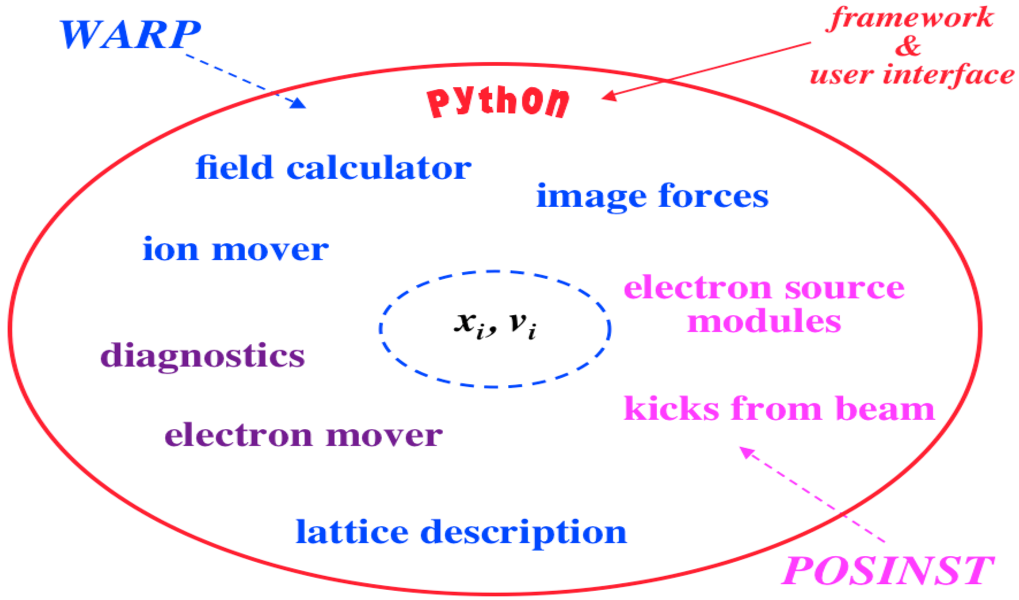
SPS - CERN

Outline

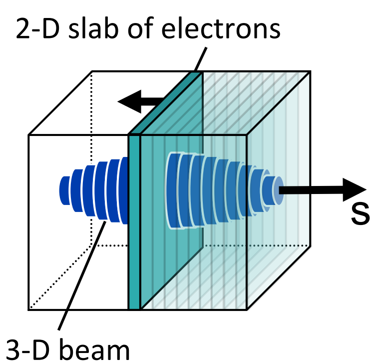
- Electron cloud effects & codes
- Recent achievements under SciDAC-II
- Plans for SciDAC-III

Under SciDAC-2, the Warp-Posinst package got further integrated

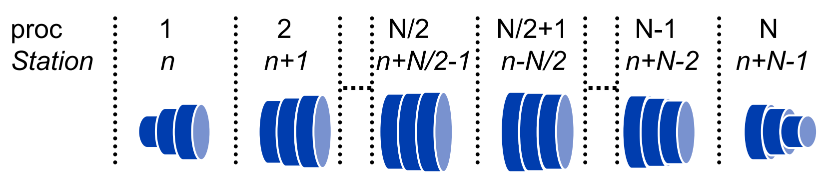
Python provides the ‘glue’ for the 2 codes

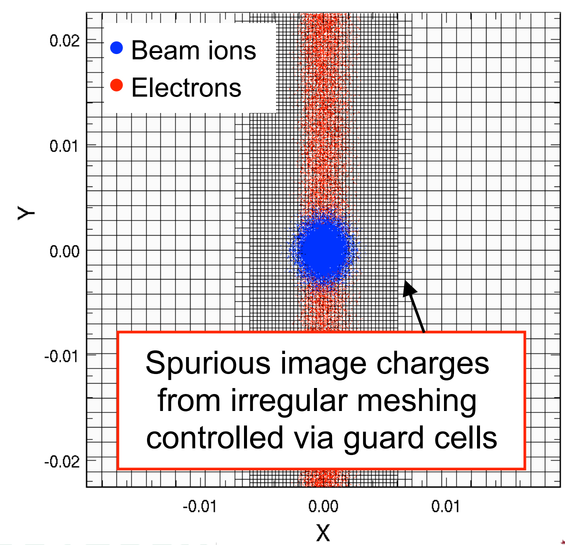


Warp’s mesh refinement & parallelism provide efficiency

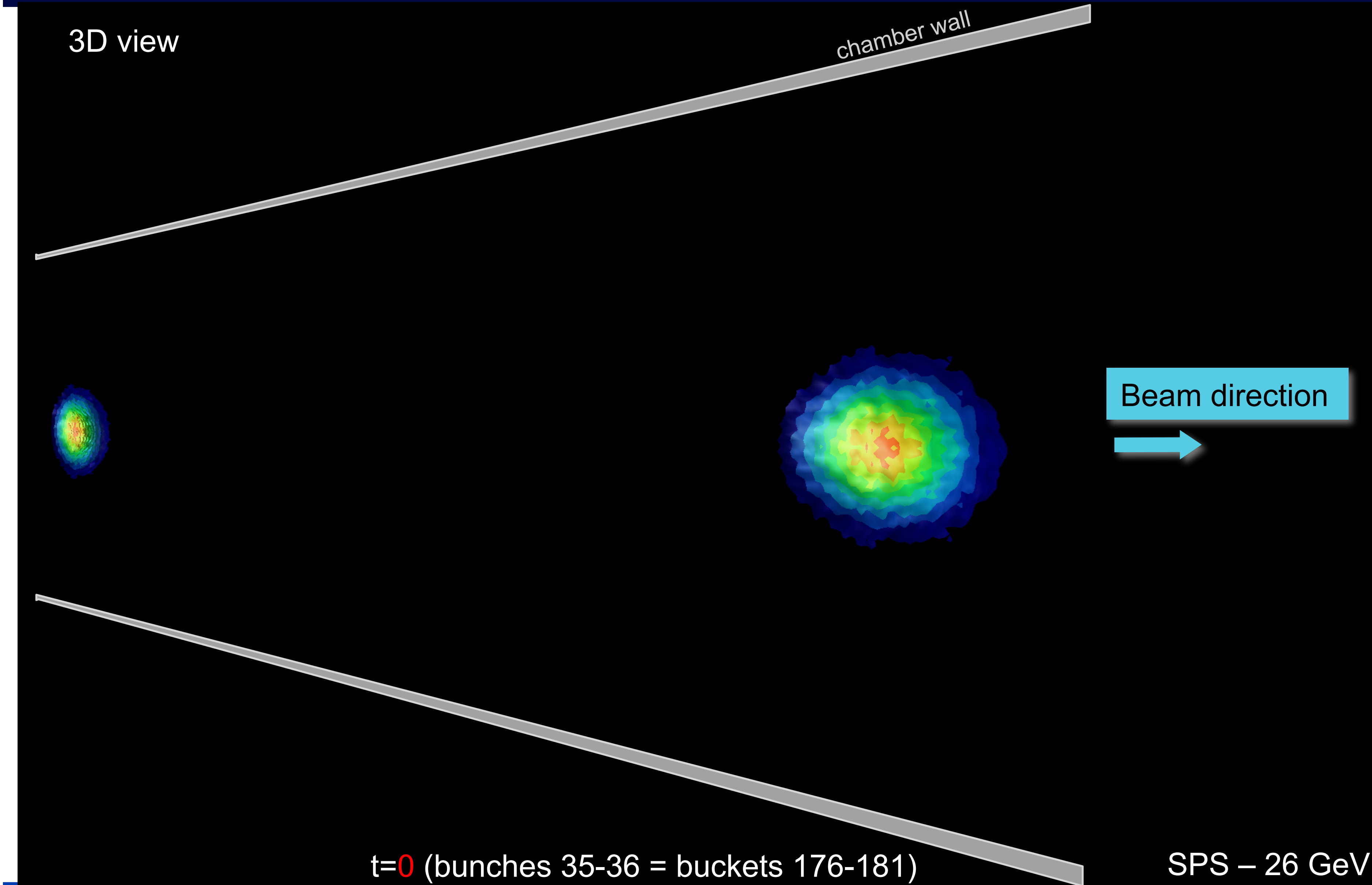


parallellized using pipelining

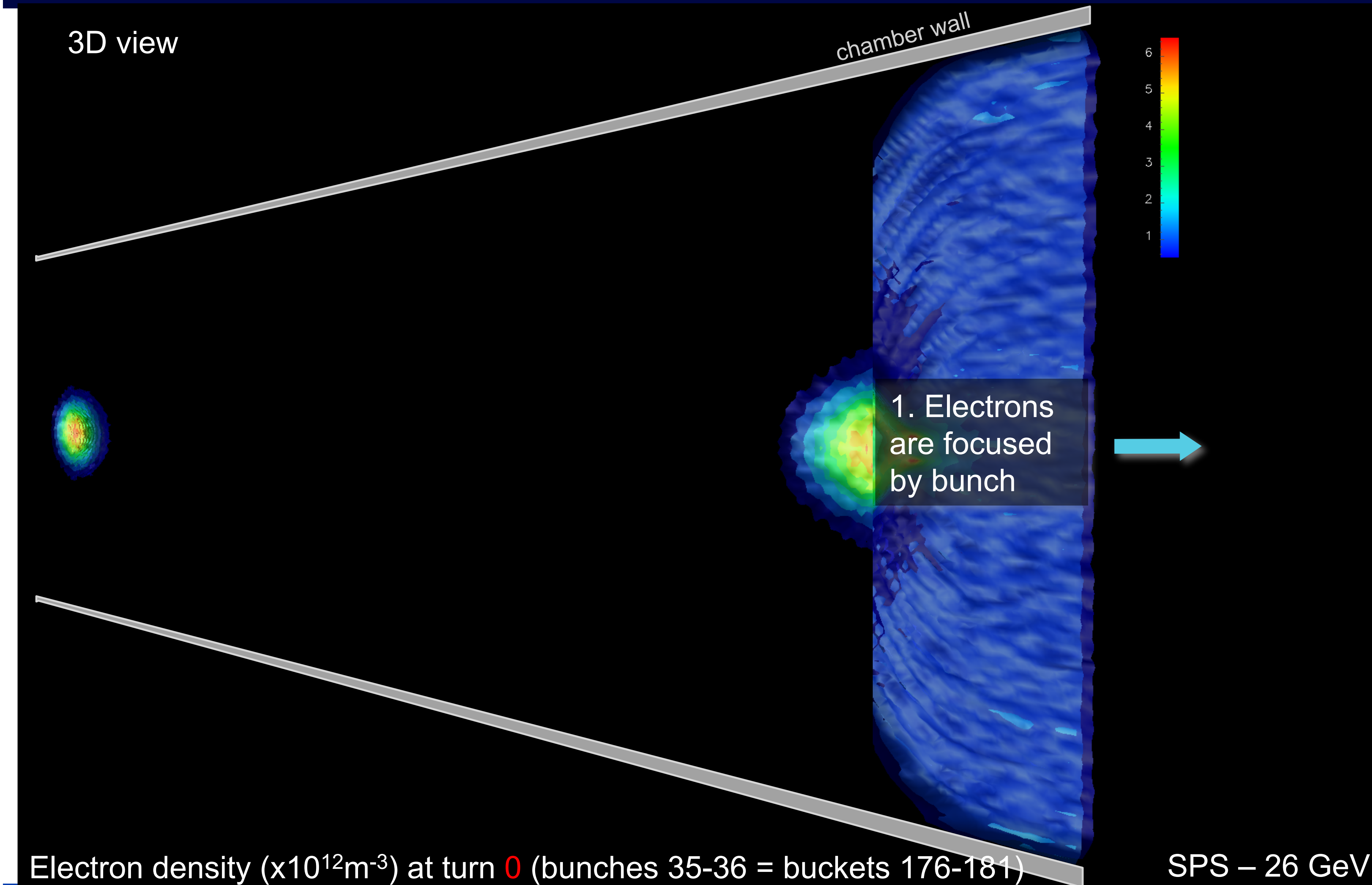




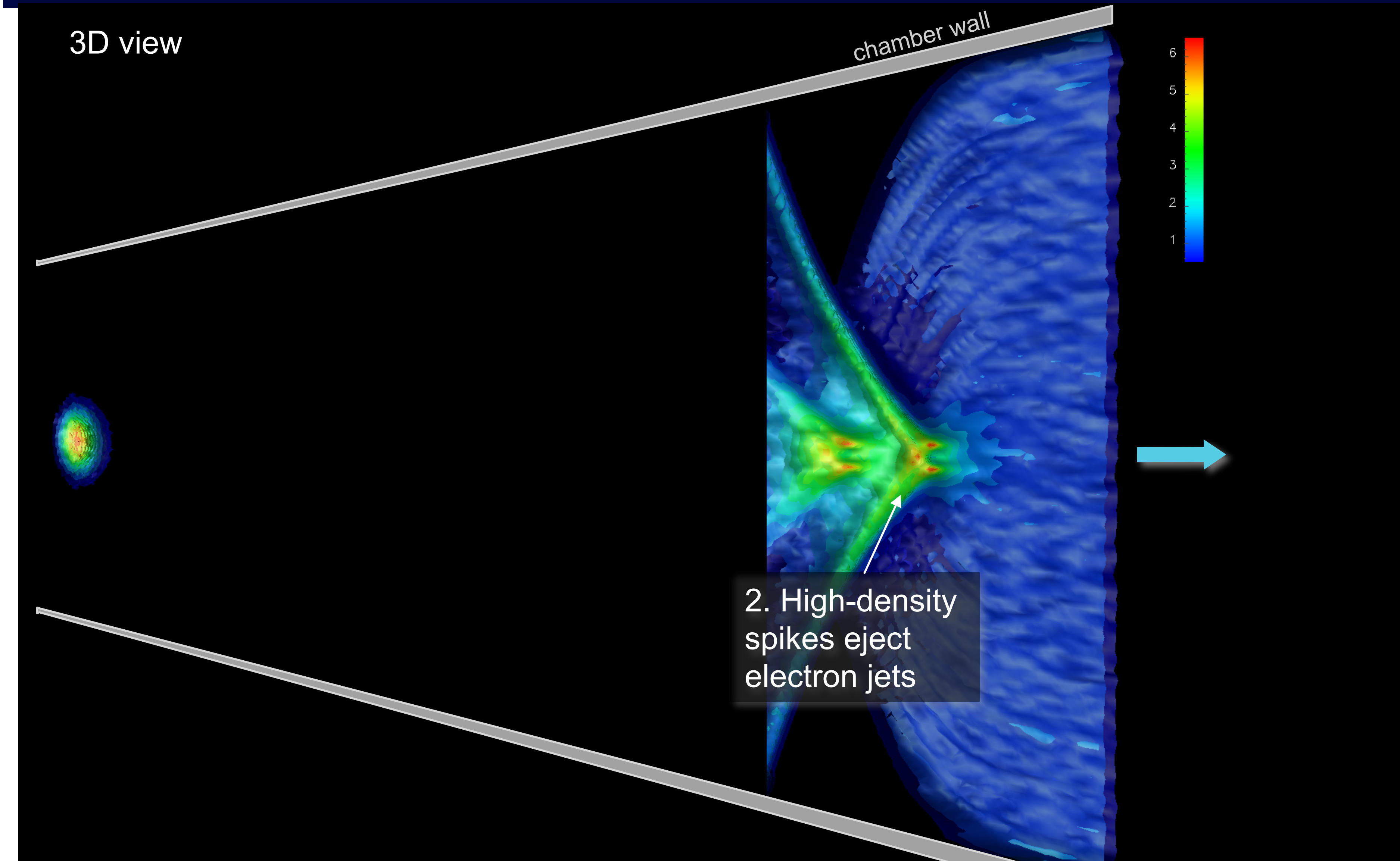
This enabled fully self-consistent simulation of e-cloud effects (build-up & beam dynamics)



Physics of electron interaction with bunches - 1



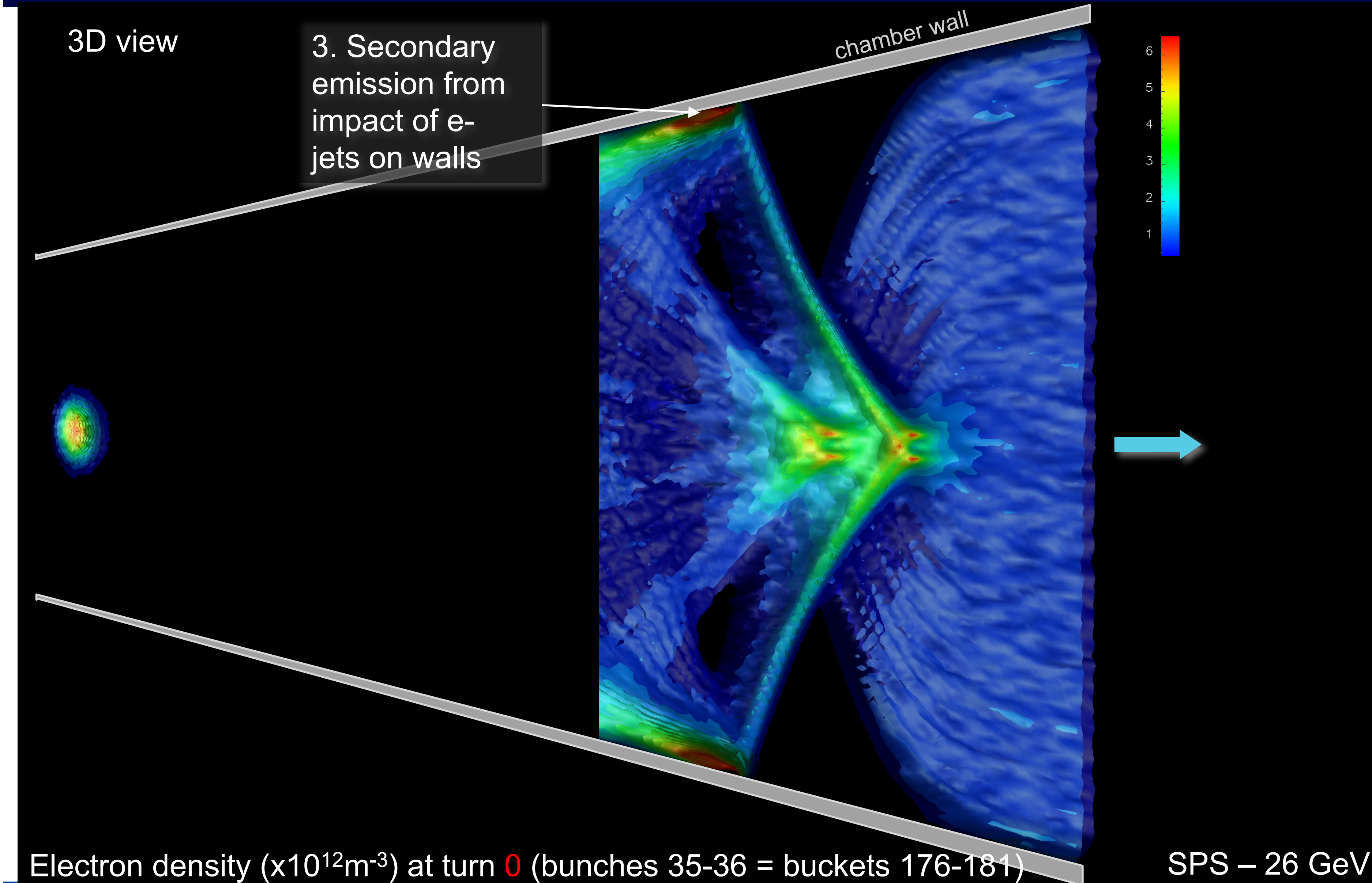
Physics of electron interaction with bunches - 2



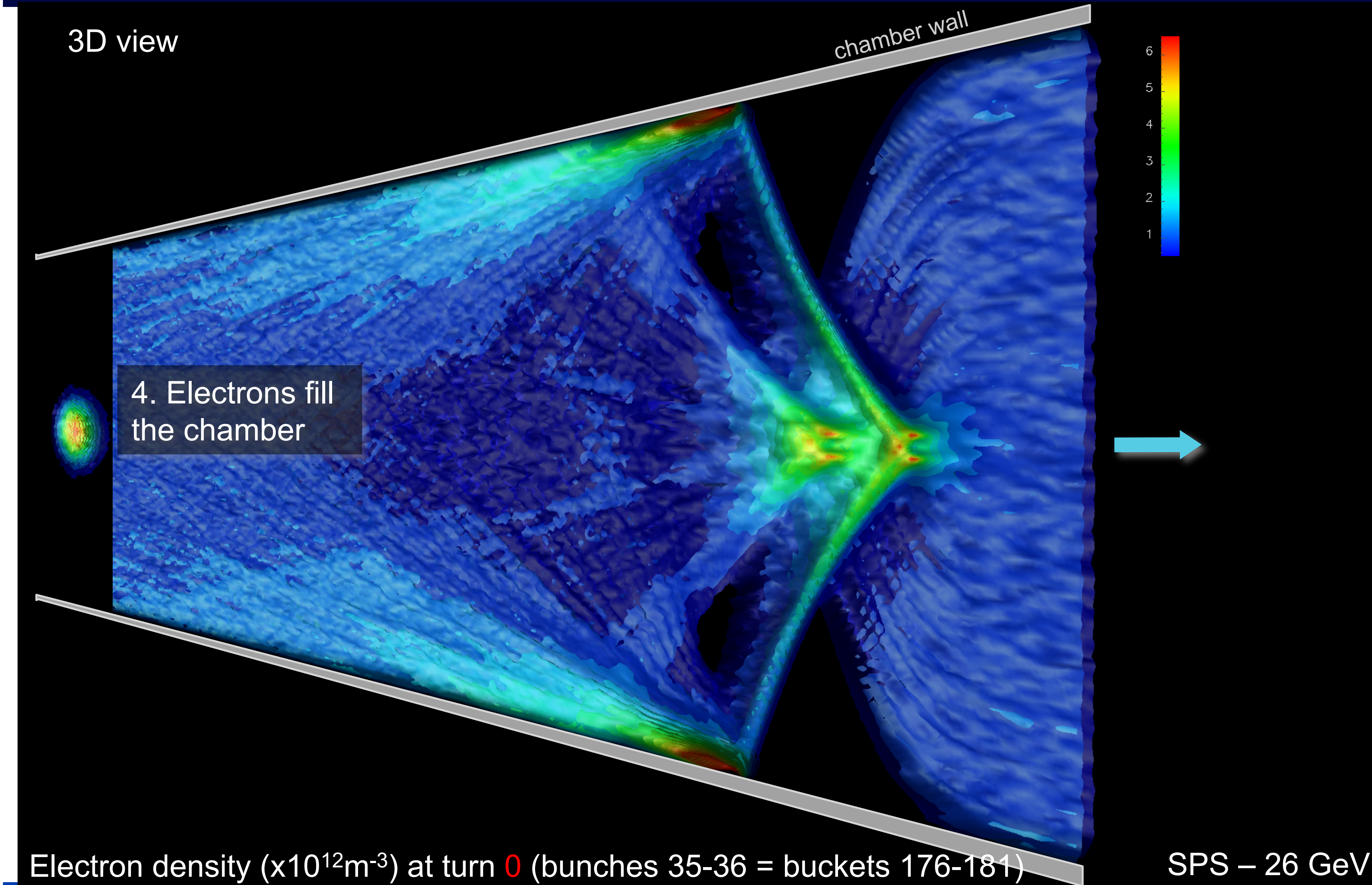
Electron density (x10^{12}m^{-3}) at turn 0 (bunches 35-36 = buckets 176-181)

SPS – 26 GeV

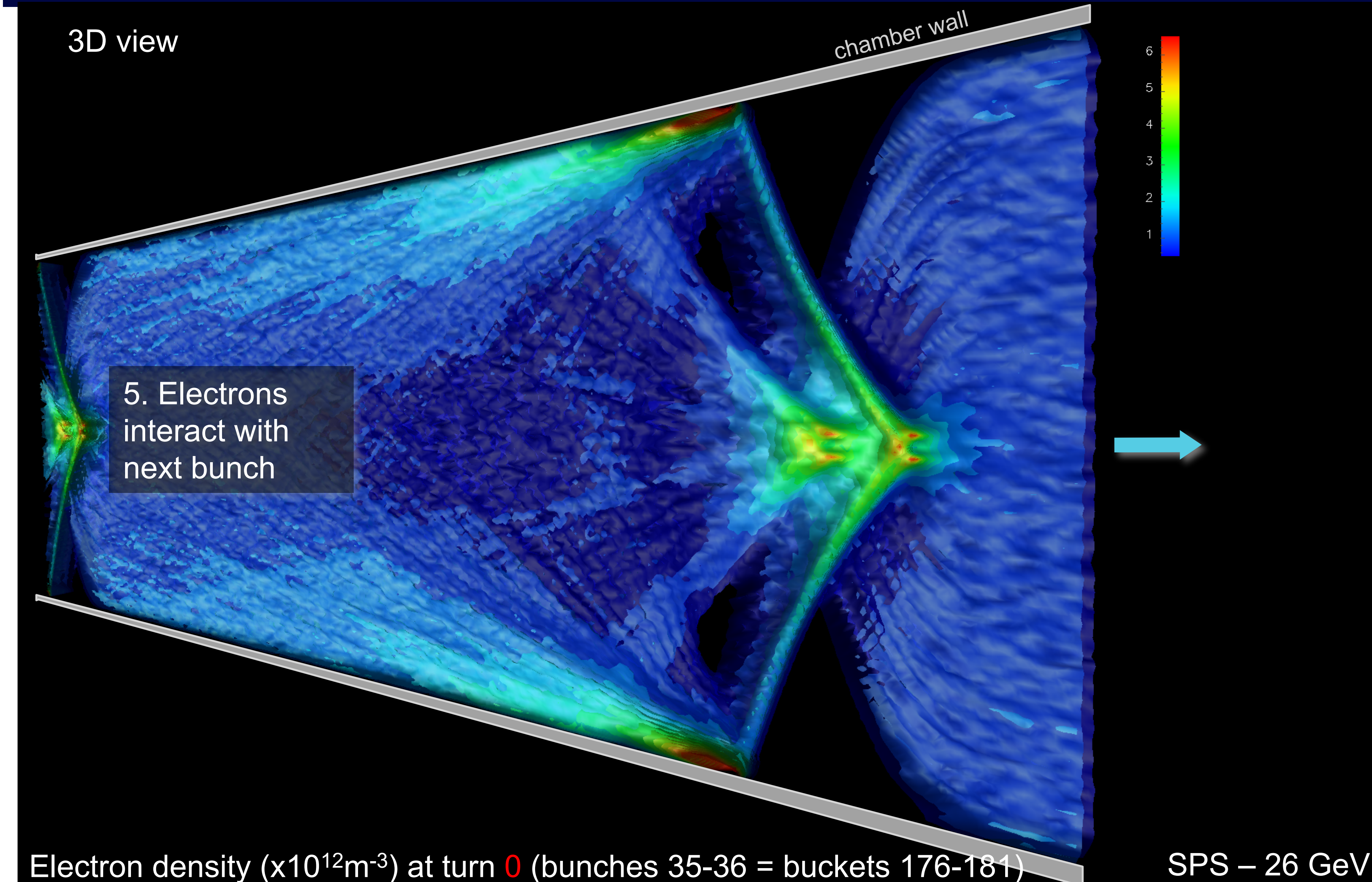
Physics of electron interaction with bunches - 3



Physics of electron interaction with bunches - 4

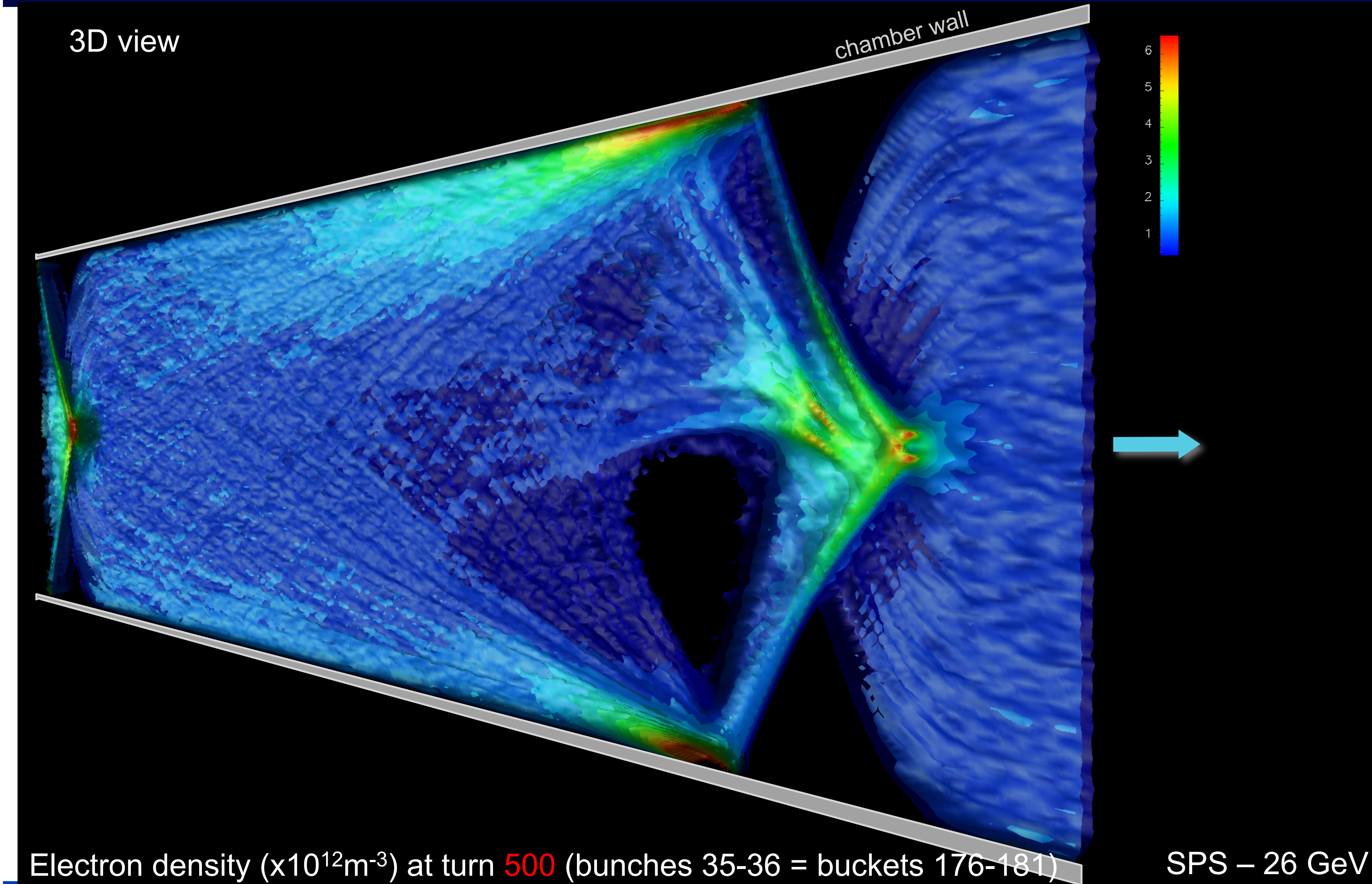


Physics of electron interaction with bunches - 5



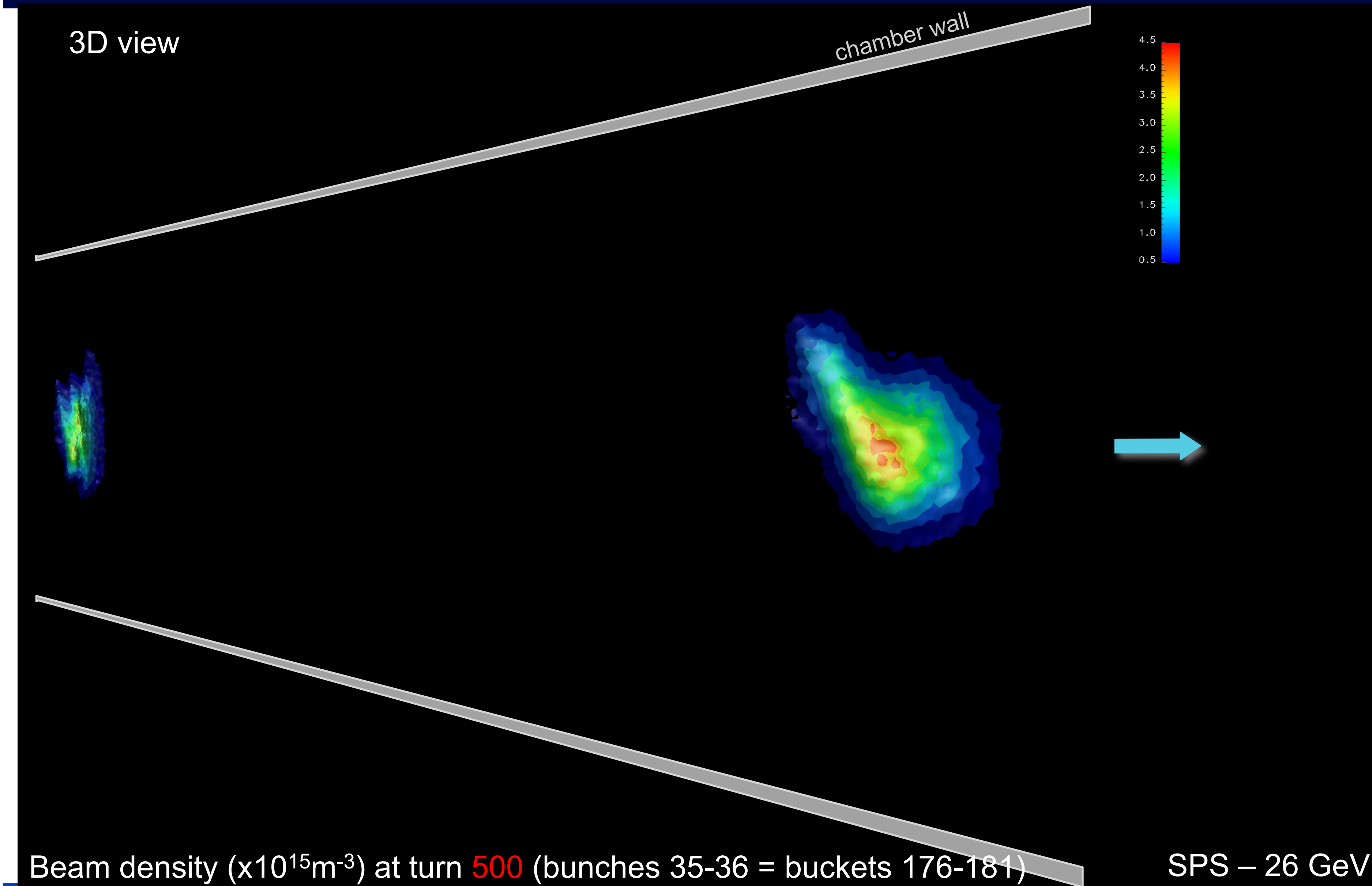
Electron density (x10^{12}m^{-3}) at turn 0 (bunches 35-36 = buckets 176-181)

Electrons after 500 turns

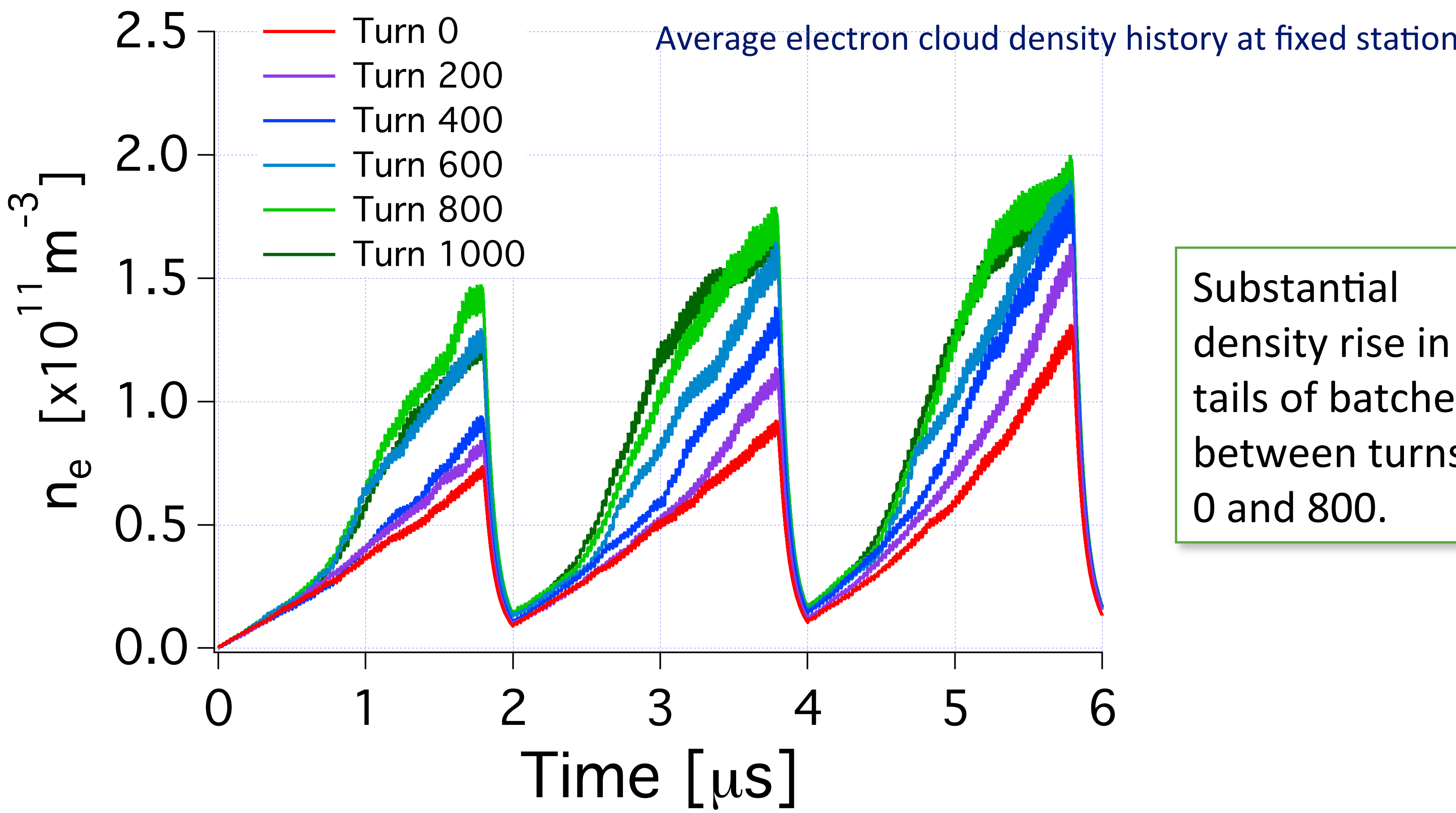


Electron density ($\times 10^{12} m^{-3}$) at turn 500 (bunches 35-36 = buckets 176-181)

Bunches 35 and 36 after 500 turns



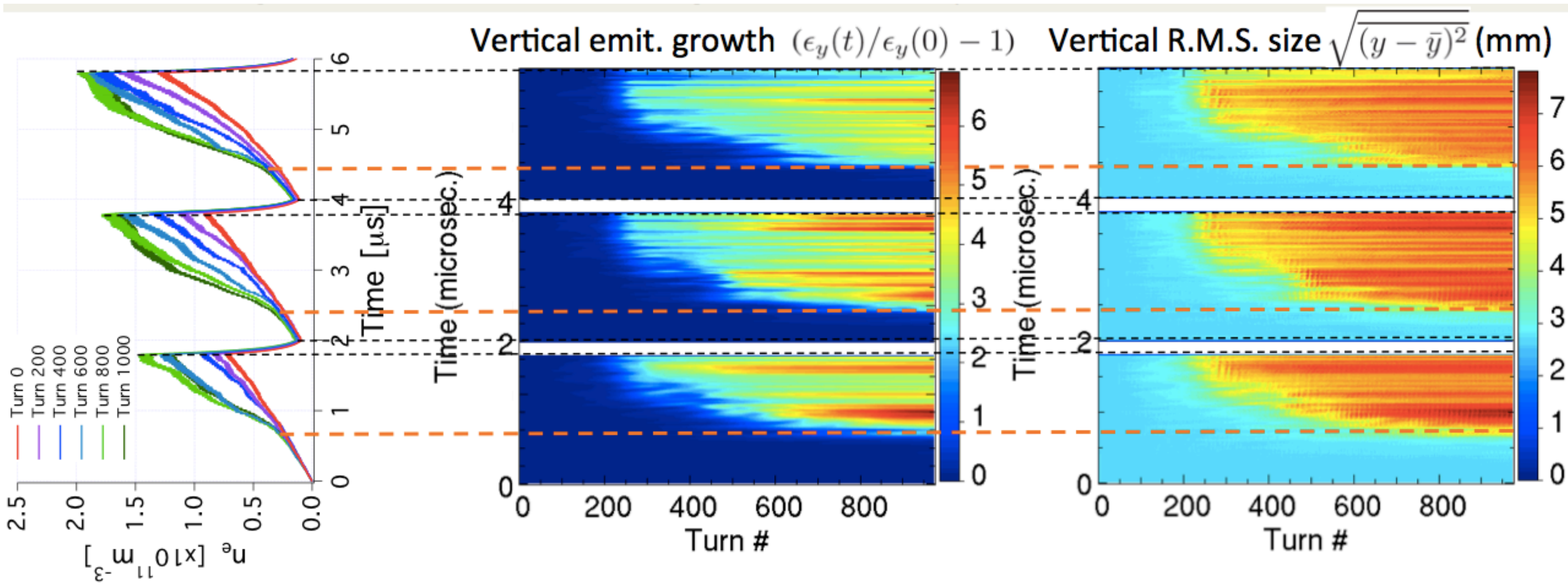
SciDAC-2: first direct simulation of a train of 3x72 bunches*
-- using 9,600 CPUs on Franklin supercomputer (NERSC, U.S.A.)



Substantial density rise in tails of batches between turns 0 and 800.

*J.-L. Vay, et al, *IPAC12 Proc.*, (2012) TUEPPB006

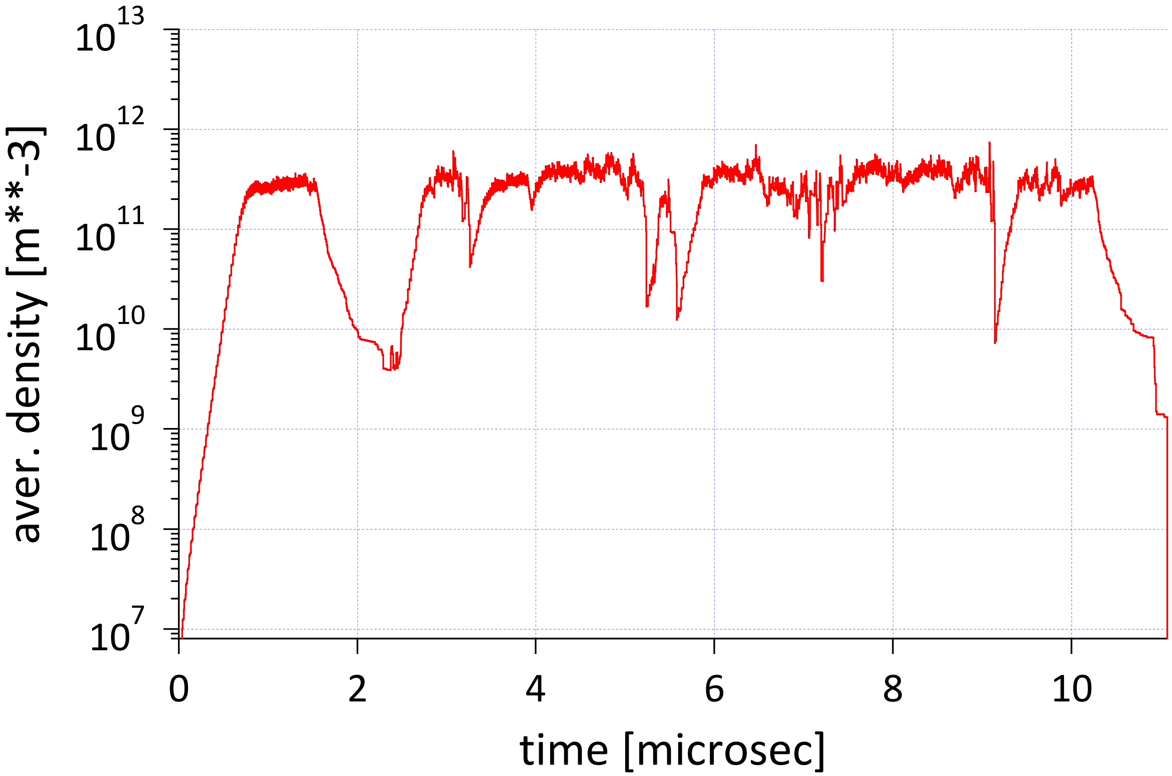
E-cloud density raise coincides with growth of vertical emittance



=> Positive coupling between the e-cloud buildup and the bunches dynamical response.

Similar effect for MI?

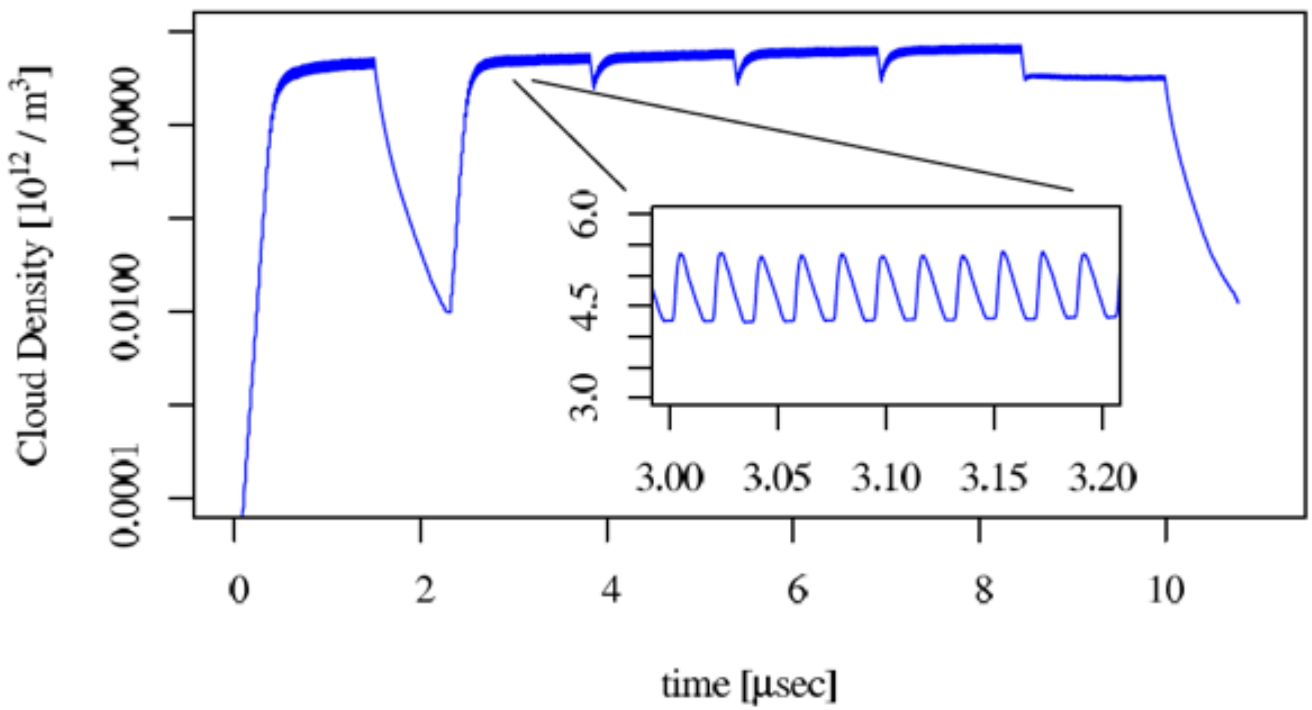
Simulations of EC buildup in MI exhibited large fluctuations



Fluctuations tentatively attibuted to physical or numerical virtual cathode.

However, Posinst simulations from P. Lebrun* were quiet
-- conditions similar but not identical to run with noise shown on previous slide

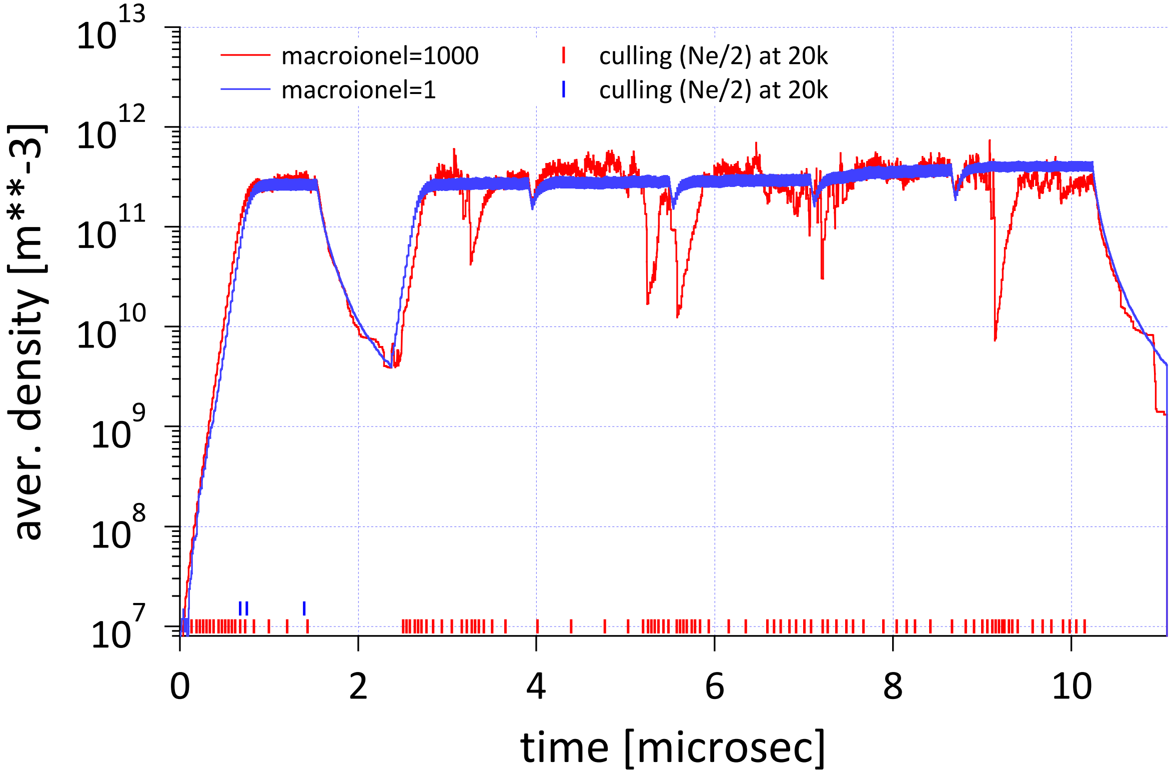
Even at lower SEY (≈ 1.4), there are no indications of sudden and seemingly chaotic change in density, i.e., no "virtual cathode" effects mentioned in reference [5].



Maximum limit of macro-electrons raised from 100k to 2M.
Higher number of macro-electrons provided quieter results.

*P. Lebrun, J. Amundson, P. Spentzouris, S. Veitzer, "A comparison and benchmark of two electron cloud packages: POSINST and VORPAL."

Recent Posinst simulations show that large fluctuations are due to wide range of macroparticle weights



Max # of macro-e$^-$ set to 20,000 in each case.

cull [kʌl] [from Old French *coillir* to pick]
3. to reduce the size of (a herd or flock) by killing a proportion of its members

Run 1 (red): 35 culling events ➔ range of weights spans $2^{35} > 10^{10}$
Run 2 (blue): 3 culling events ➔ range of weights spans $2^{3} < 10$

➔ Culling events need to be scarce by setting high threshold or raising floor of weight values.

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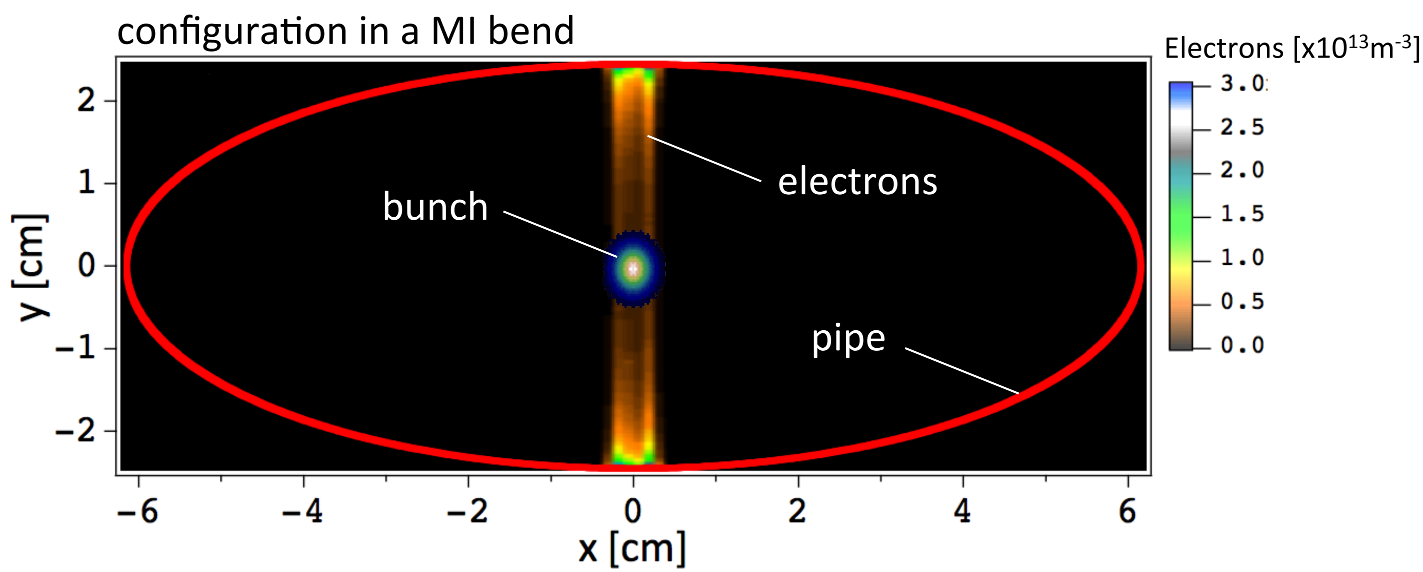
- Plans for SciDAC-III

Plans for SciDAC-3

- 2013: mesh refinement (Warp); benchmarking vs Posinst & Vorpal



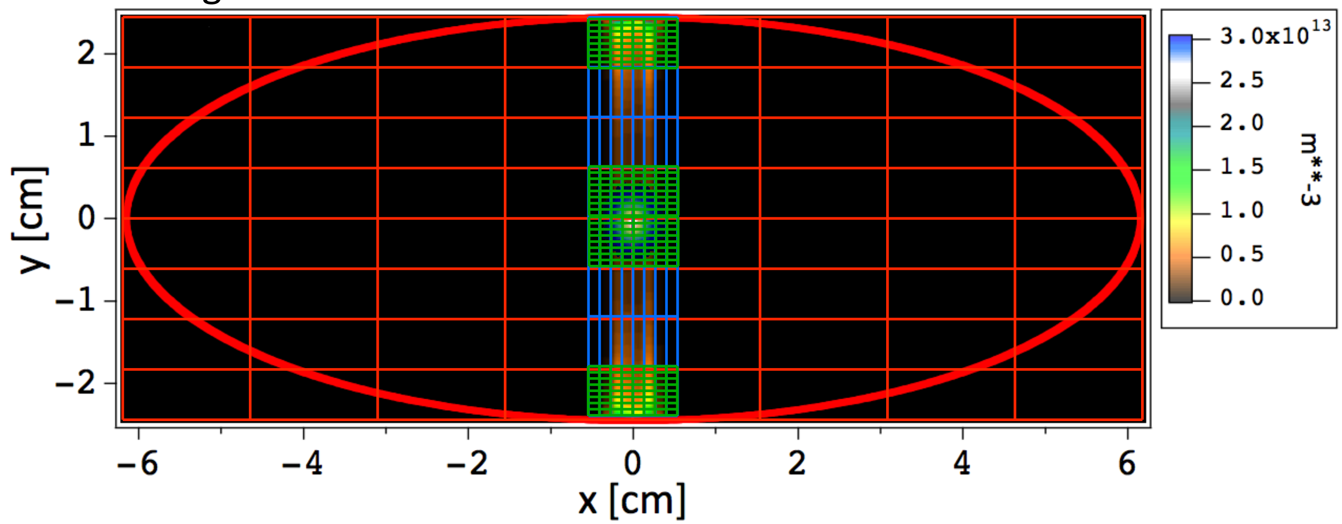
- 2014: study and improve adaptive macro-particle management (splitting, culling, coalescence)

- 2015: high fidelity fully self-consistent modeling of electron cloud effects on bunch train in MI; benchmarking w/ Synergia & expt

Plans for SciDAC-3

- 2013: mesh refinement (Warp); benchmarking vs Posinst & Vorpal

configuration in a MI bend



- 2014: study and improve adaptive macro-particle management (splitting, culling, coalescence)

- 2015: high fidelity fully self-consistent modeling of electron cloud effects on bunch train in MI; benchmarking w/ Synergia & expt

Questions about Posinst, contact:

Miguel Furman (MAFurman@lbl.gov)

Questions about Warp, contact:

David Grote (DPGrote@lbl.gov)

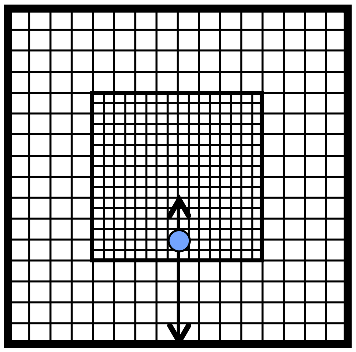
Jean-Luc Vay (JLVay@lbl.gov)

Alex Friedman (AFriedman@lbl.gov)

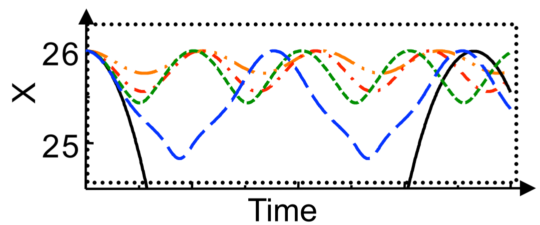
Extra Slides

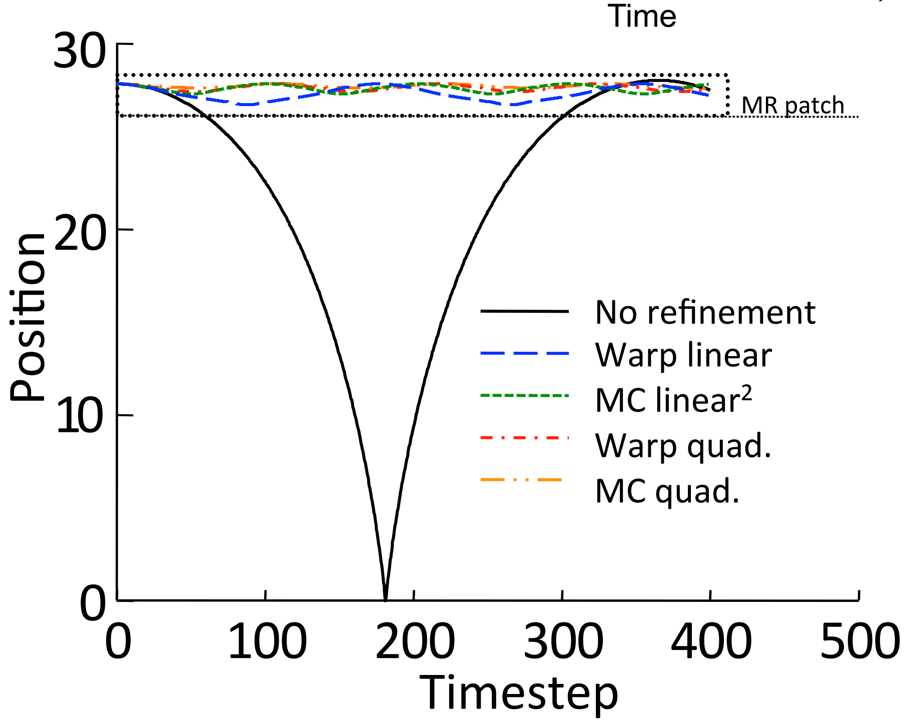
Electrostatic mesh refinement method: spurious self-force

MR introduces spurious self-force[1]



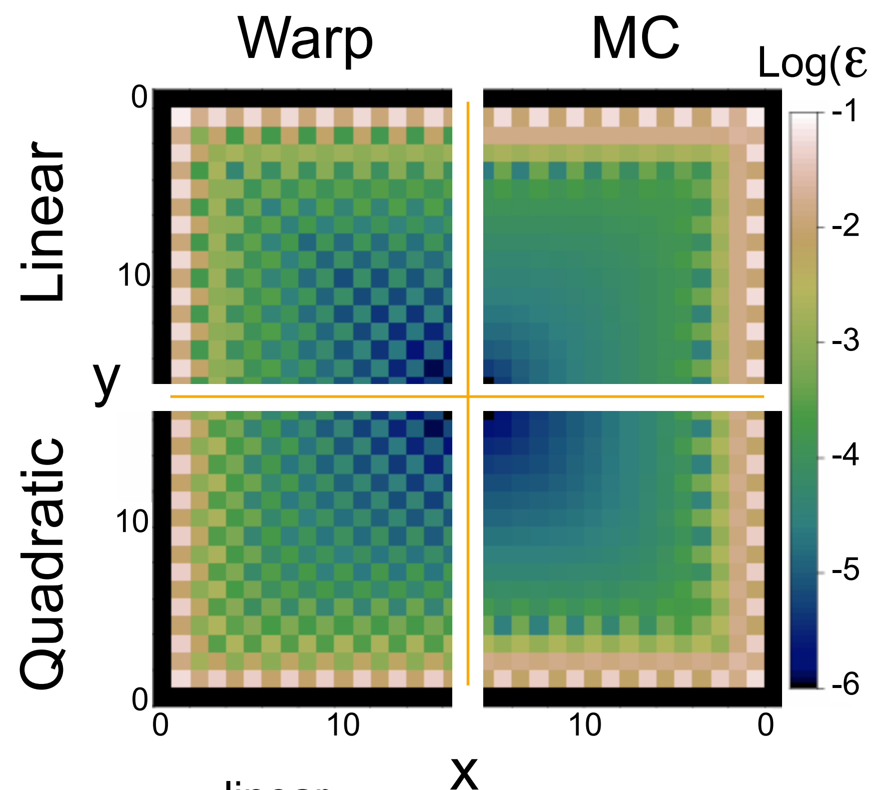
particle feels its own field and can be trapped in patch

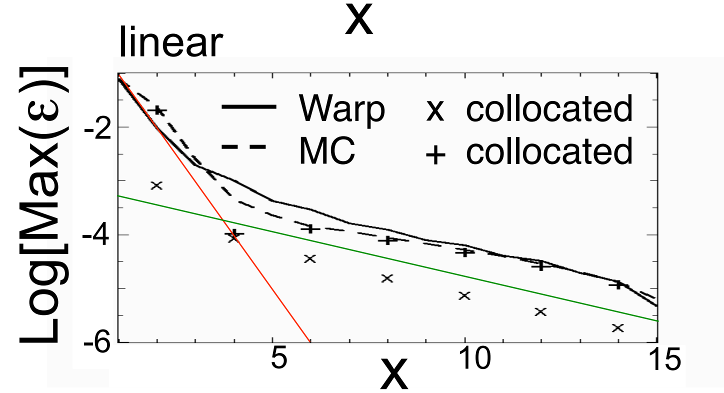




(1) Vay et al., *Laser Part. Beams* **20** (2002)
(2) McCorquodale et al., *J. Comput. Phys.* **201** (2004)

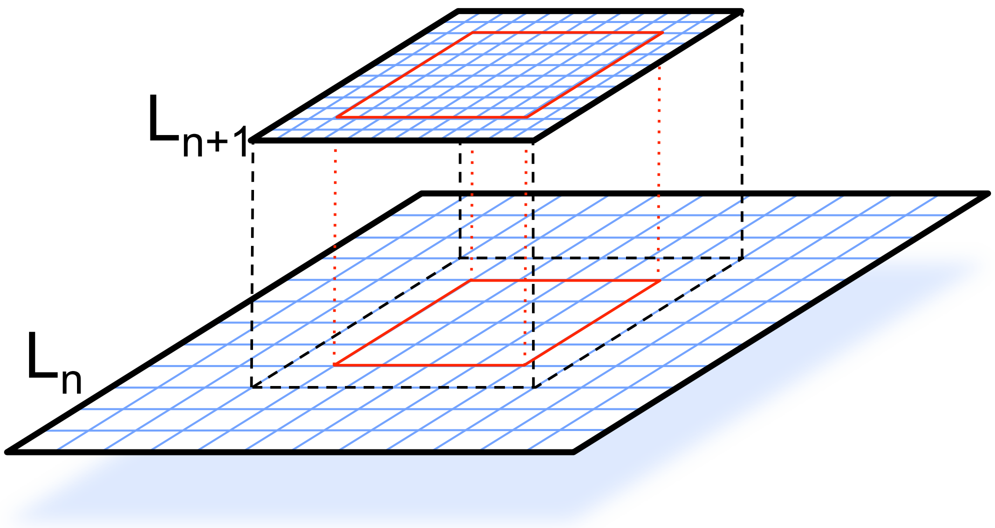
Spurious self-force decreases rapidly in patch





Spurious self-force mitigated in Warp using guard cells

Warp's electrostatic MR solver[1,2]

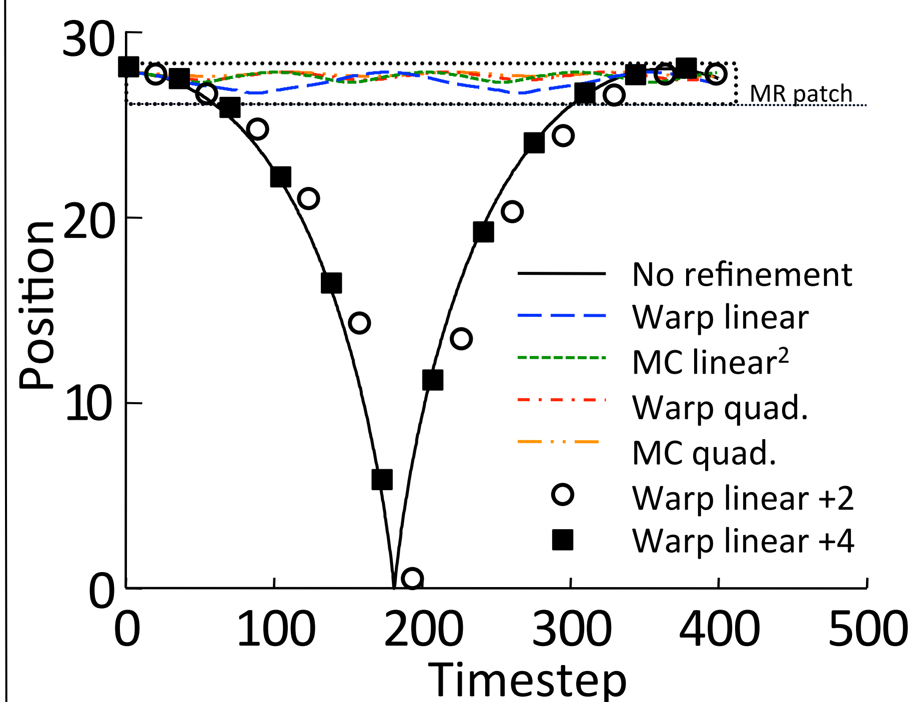


1 – solve on coarse grid,
2 – interpolate on fine grid boundaries,
3 – solve on fine grid,
4 – disregard fine grid solution close to edge when gathering force onto particles.

Guard cells provide user control of relative magnitude of spurious force[(2)].

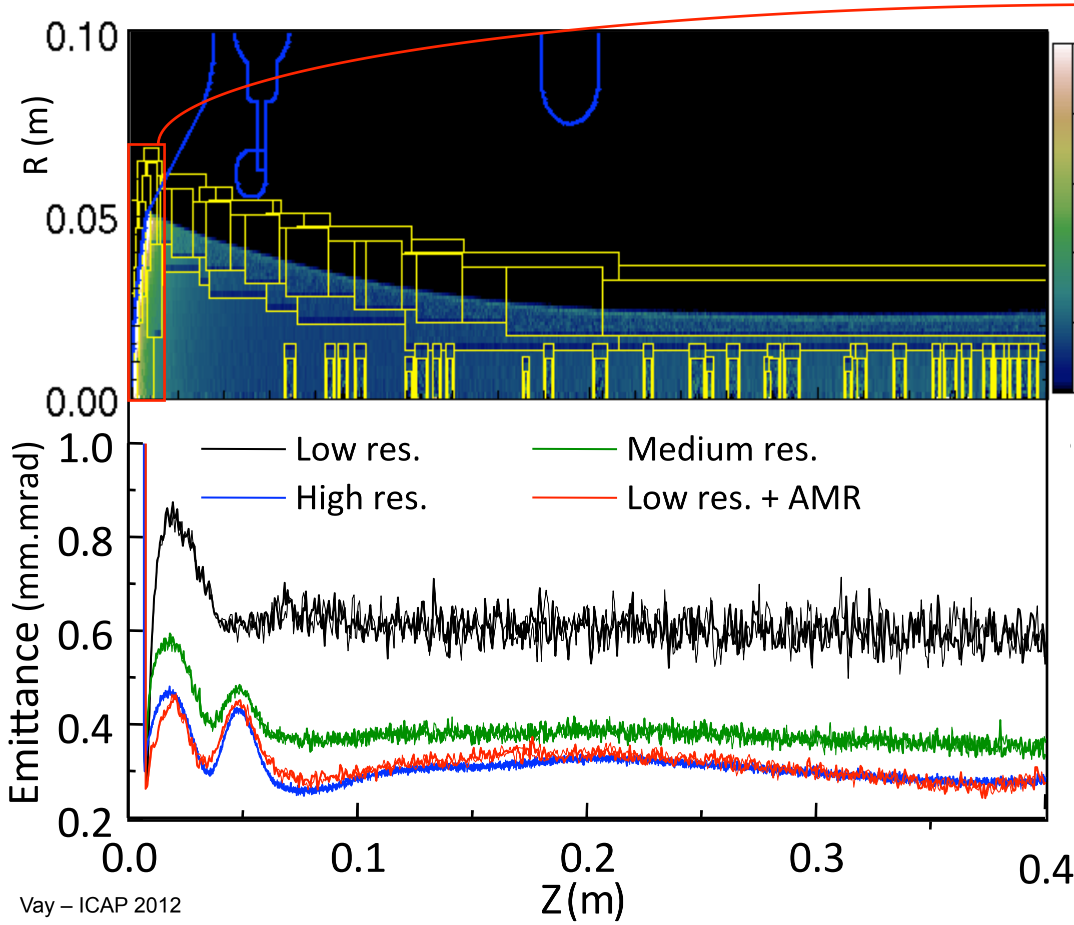
(1) Vay et al., *Laser Part. Beams* **20** (2002)
(2) Vay et al., *Phys. Plasmas* **11** (2004)

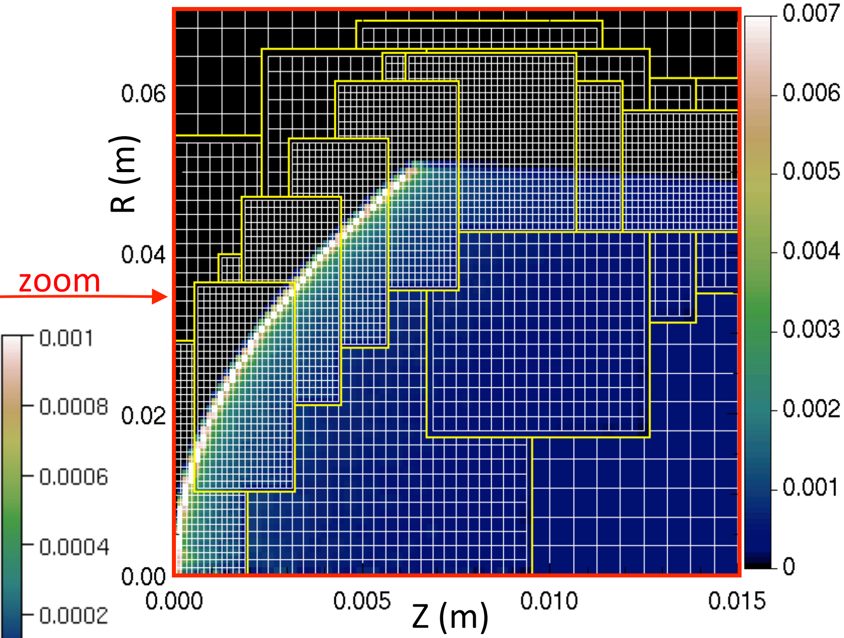
Example with 2 and 4 guard cells

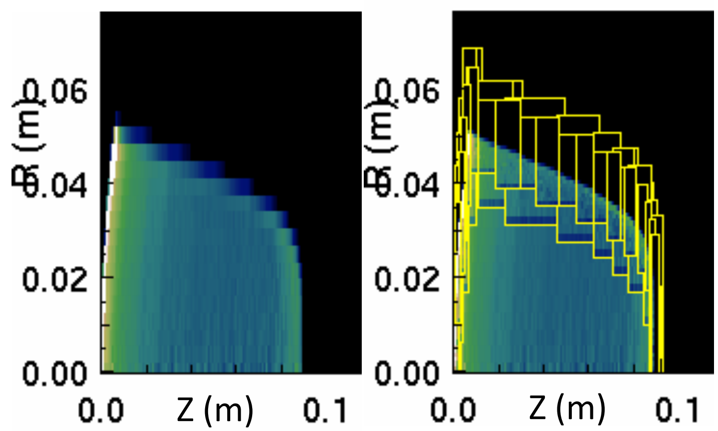


Example of application to AMR simulations of ion source
-- speedup from AMR x10

Run	Grid size	Nb particles
Low res.	56 x 640	~1M
Medium res.	112 x 1280	~4M
High res.	224 x 2560	~16M
Low res. + AMR	56 x 640	~1M





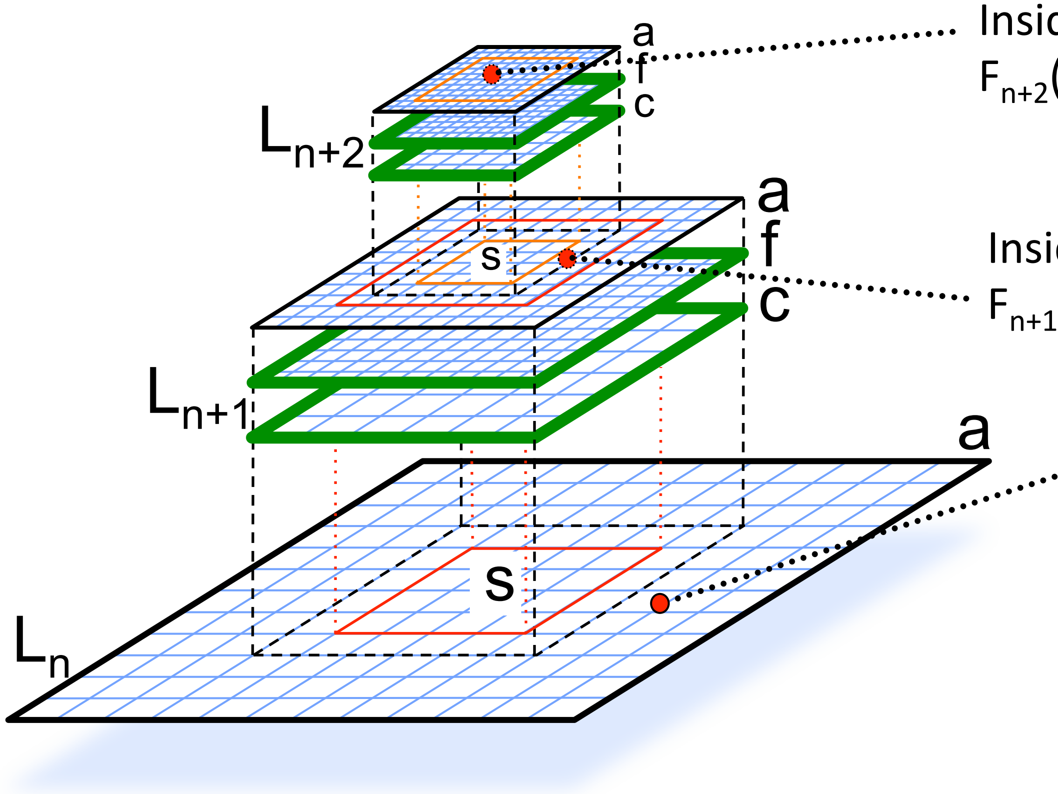


Automatic mesh refinement follows gradients: emitting area, beam edge and front.

Warp's Electromagnetic MR uses PML & substitution to prevent reflections

Warp's electromagnetic MR solver

- Termination of patches with PML avoids spurious reflections
- Guard cell used for mitigating spurious self-force



Inside patch at L_{n+2}:
$F_{n+2}(a) = \mathrm{I}[F_{n+1}(s)-F_{n+2}(c)]+F_{n+2}(f)$

Inside patch at L_{n+1}:
$F_{n+1}(a) = \mathrm{I}[F_{n}(s)-F_{n+1}(c)]+F_{n+1}(f)$

Main grid: $F_n(a)$

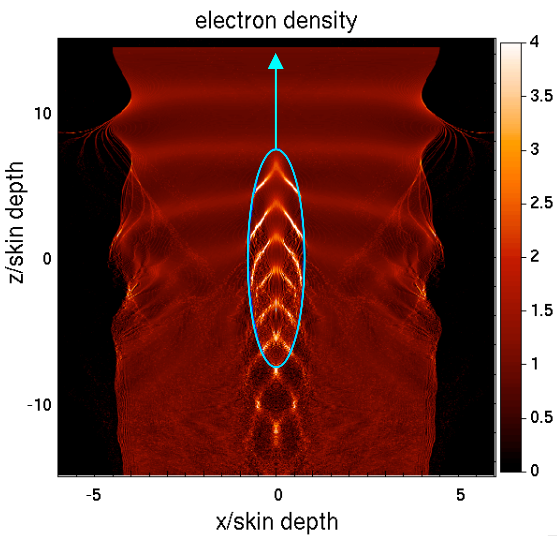
- absorbing layer (PML)
- a = auxilliary
- f = fine
- c = coarse

*Vay, Adam, Heron, *Comp. Phys. Comm.* 164 (2004)

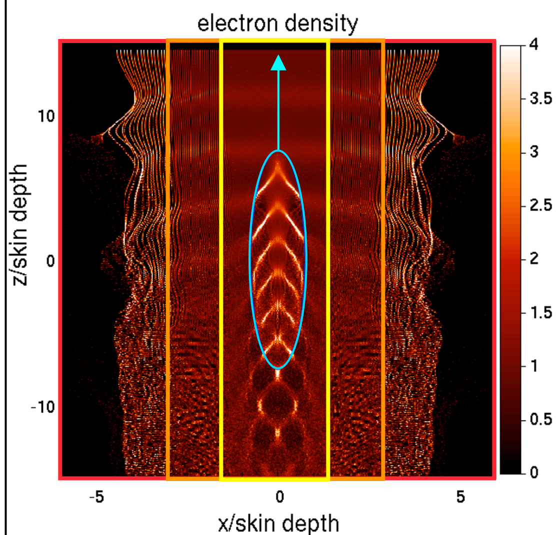
Electromagnetic MR simulation of beam-induced plasma wake

no refinement | 2 levels of mesh refinement (MR)

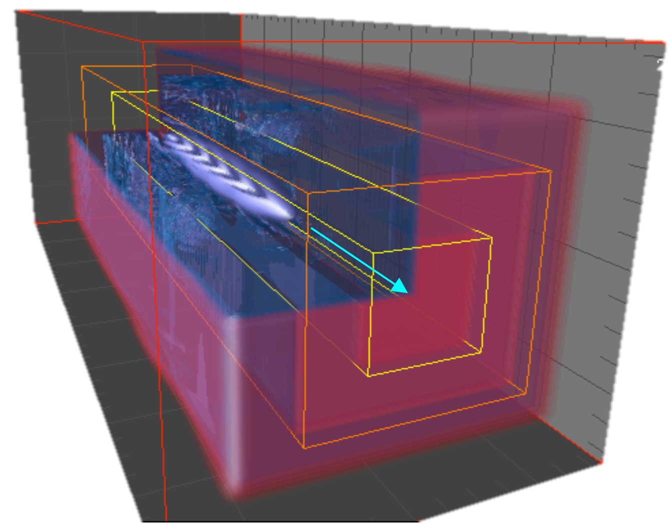
2-D high resolution



2-D low resolution + MR

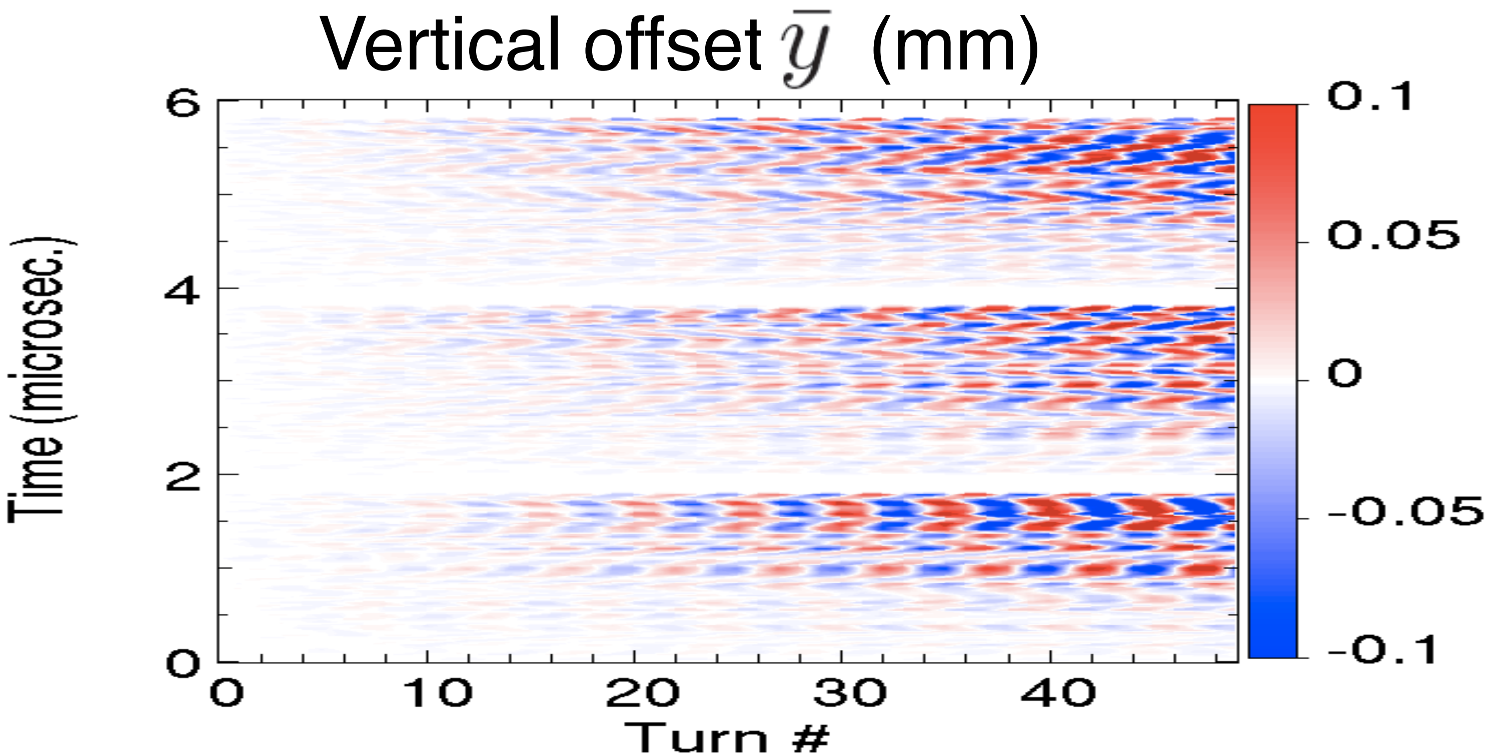


3-D



Speedup x10 in 3D (using the same time steps for all refinement levels).

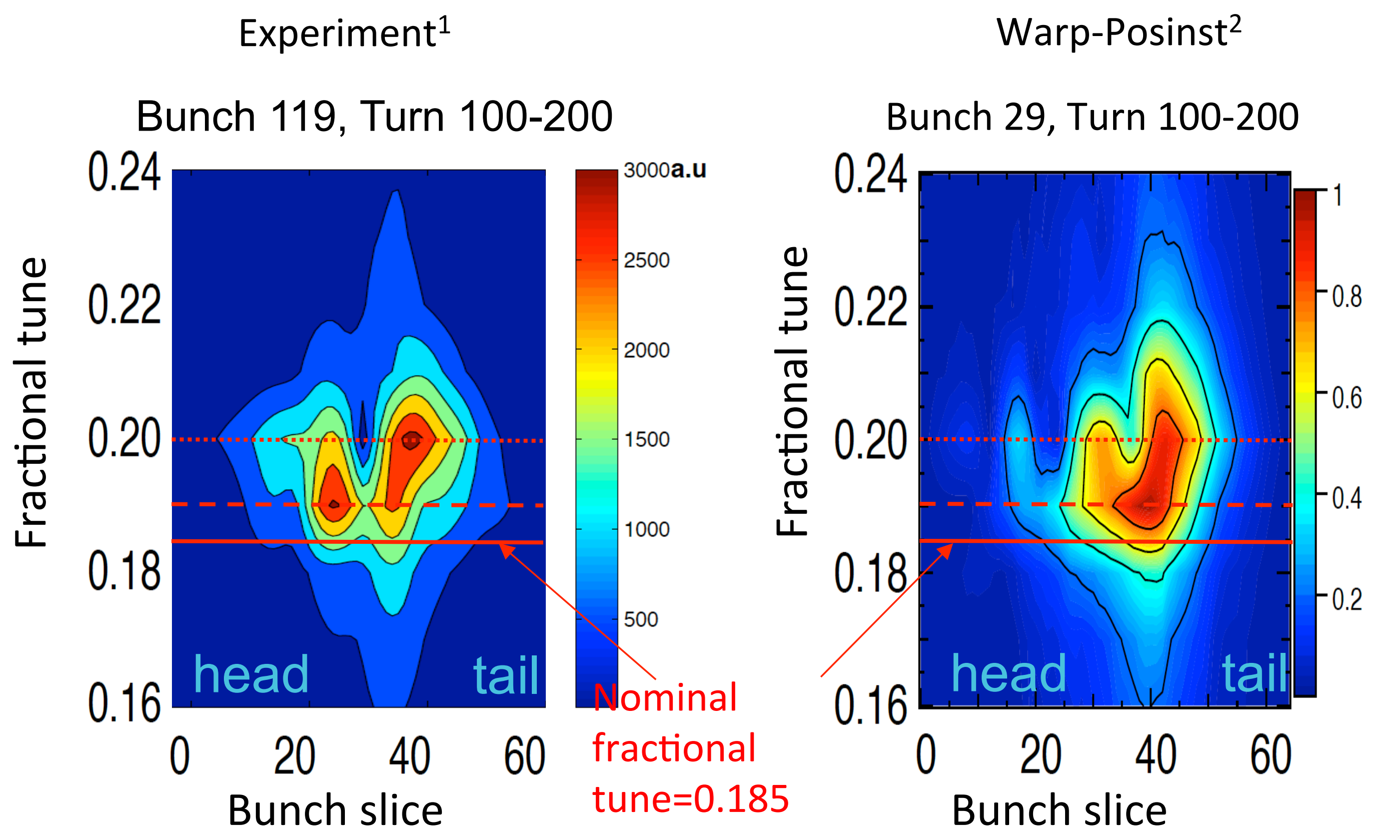
Pattern of stripes in the history of vertical bunch offsets



$\Rightarrow$ phase of the oscillations is not purely random

E-cloud provides coupling between bunches.

Comparison with experimental measurements
-- collaboration with SLAC/CERN

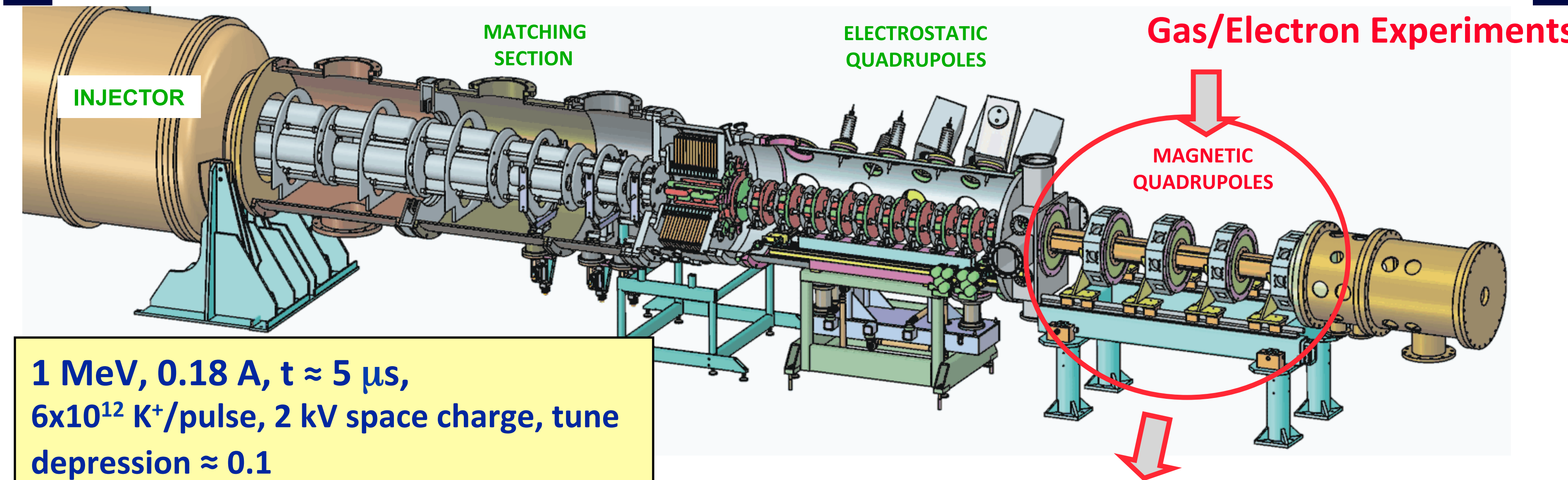


[1]J. Fox, et al, *IPAC10 Proc.*, p. 2806 (2011)   [2]J.-L. Vay, et al, *Ecloud10 Proc.*, (2010)

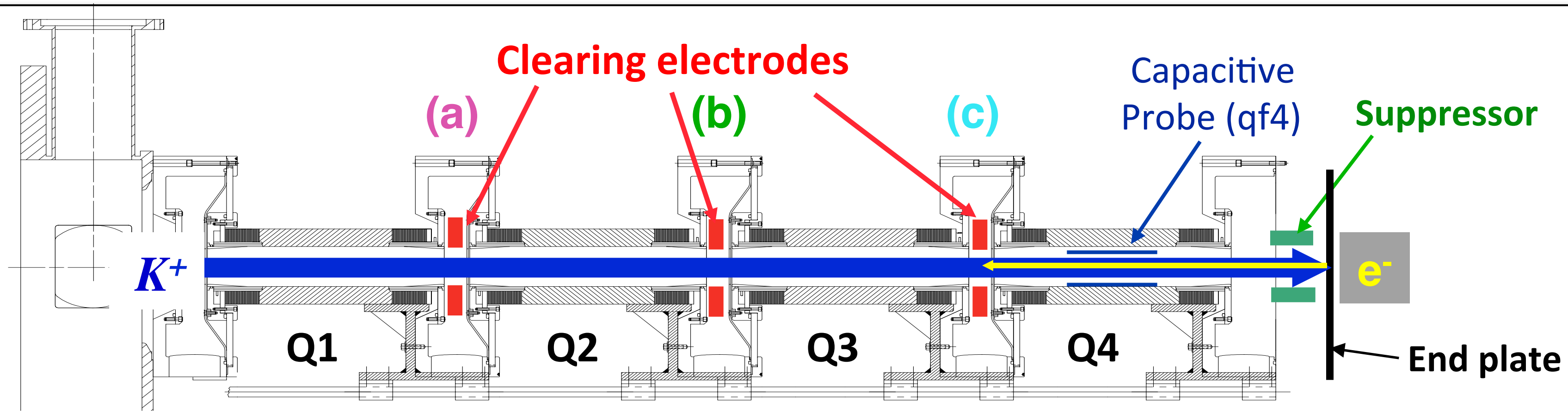
Good qualitative agreement: separation between core and tail with similar tune shift.

Warp is also applied to study of feedback control system (R. Secondo in collaboration with SLAC)

Benchmarked against dedicated experiment on HCX

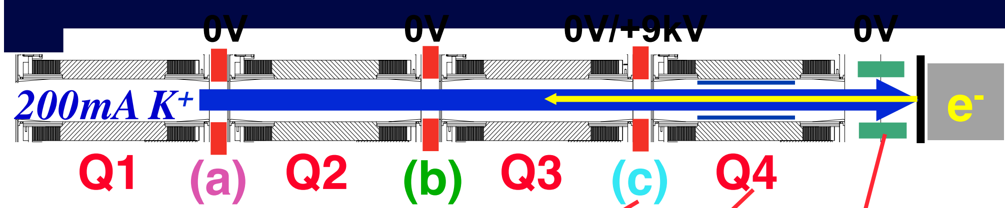


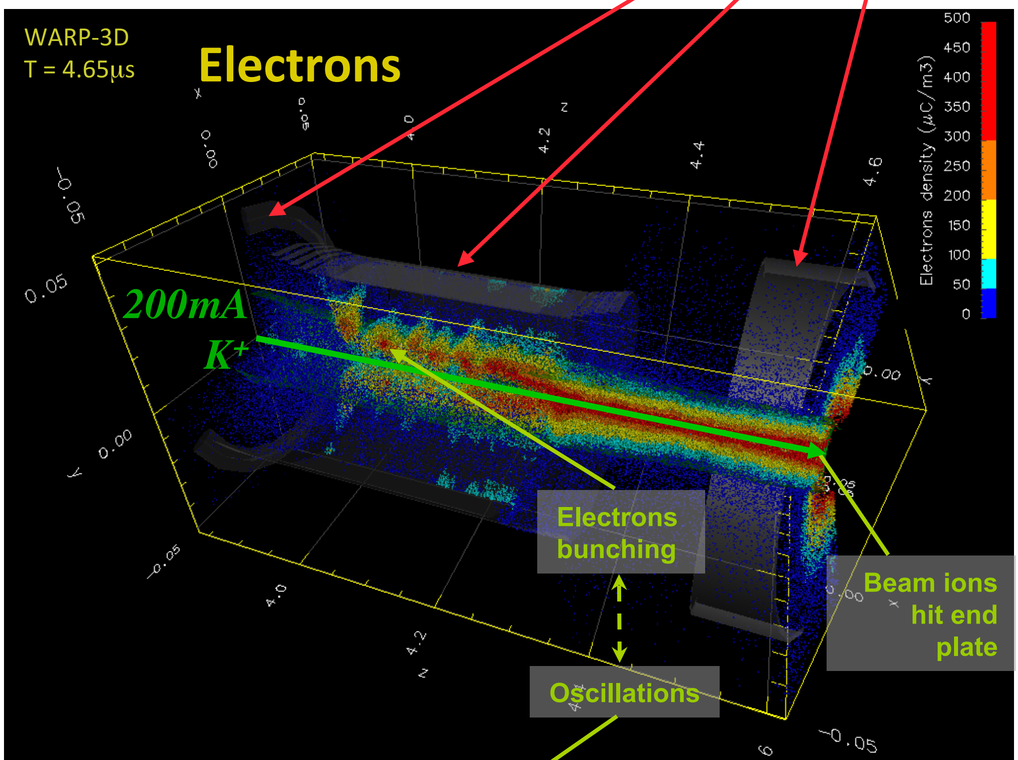
1 MeV, 0.18 A, t ≈ 5 μs,
$6\mathrm{x}10^{12}$ K^+/pulse, 2 kV space charge, tune depression ≈ 0.1

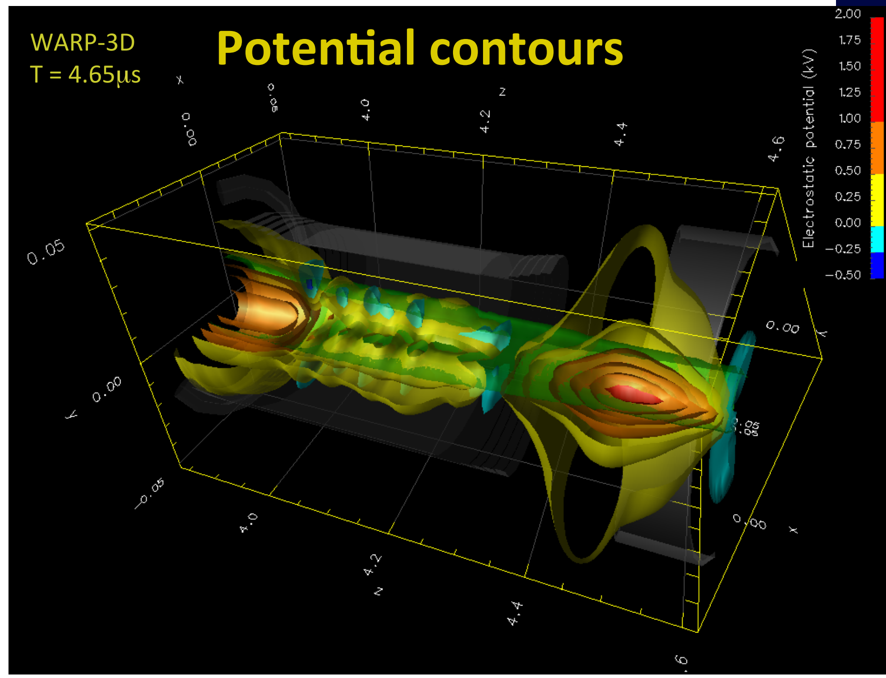


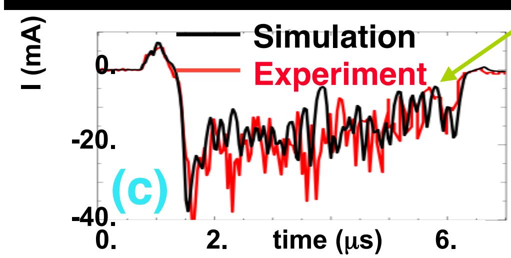
Short experiment => need to deliberately amplify electron effects:
let beam hit end-plate to generate copious electrons which propagate upstream.

Detailed exploration of dynamics of electrons in quadrupole



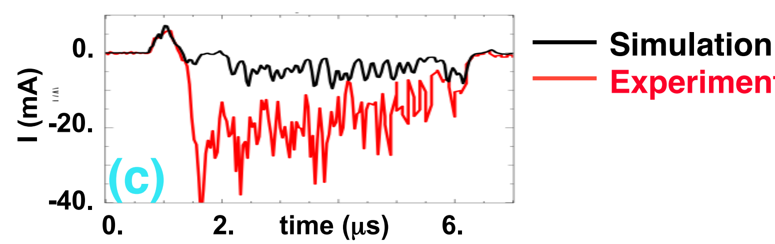






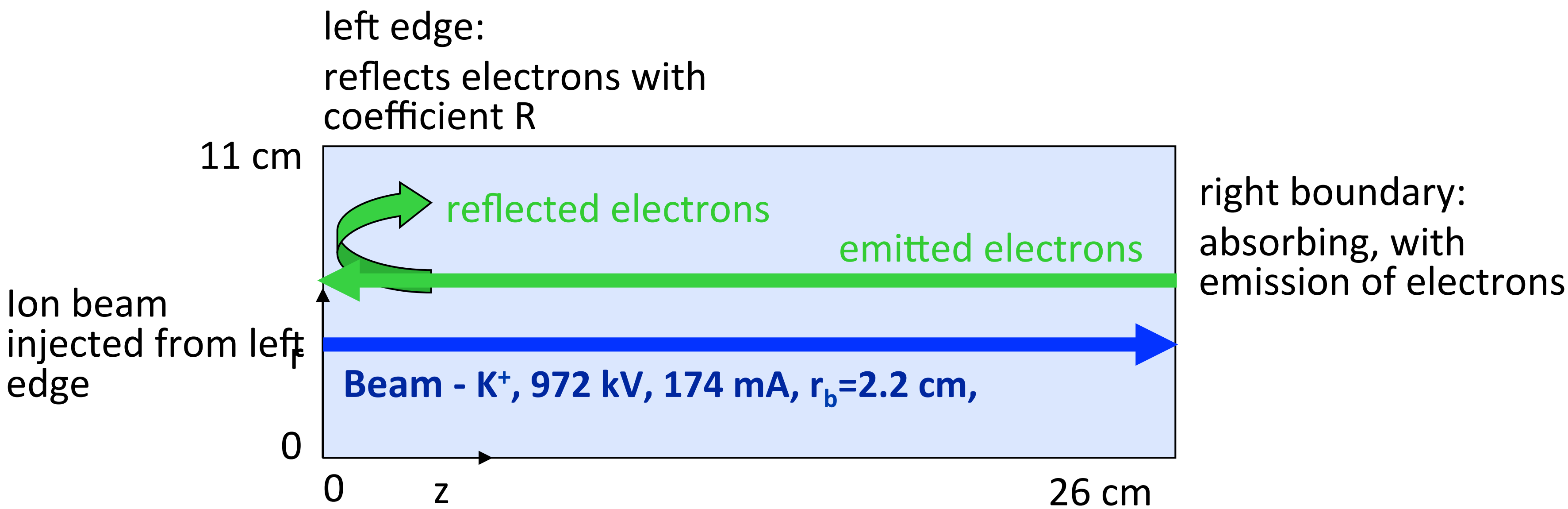
~6 MHz signal in (C) in simulation & experiment

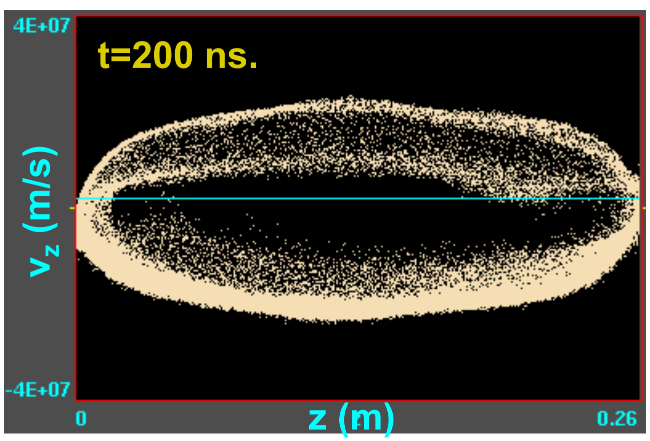
1. **Importance of secondaries** - if secondary electron emission turned off:

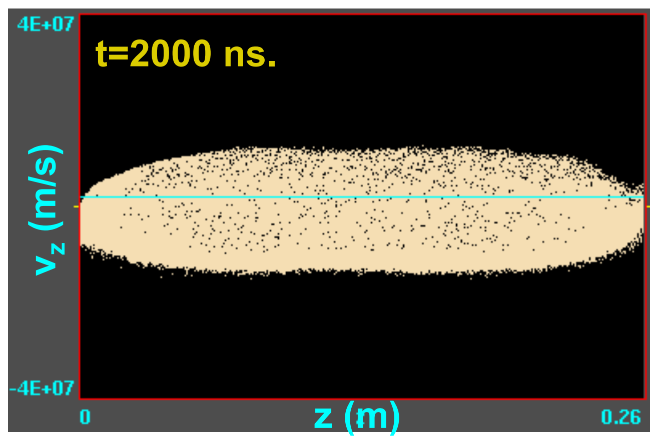


2. **run time ~3 days**
   - without new electron mover and MR, run time would be ~1-2 months!

Study of virtual cathode using axisymmetric XOOPIC[1] model







Phase space hole eventually collapses due to VC oscillations

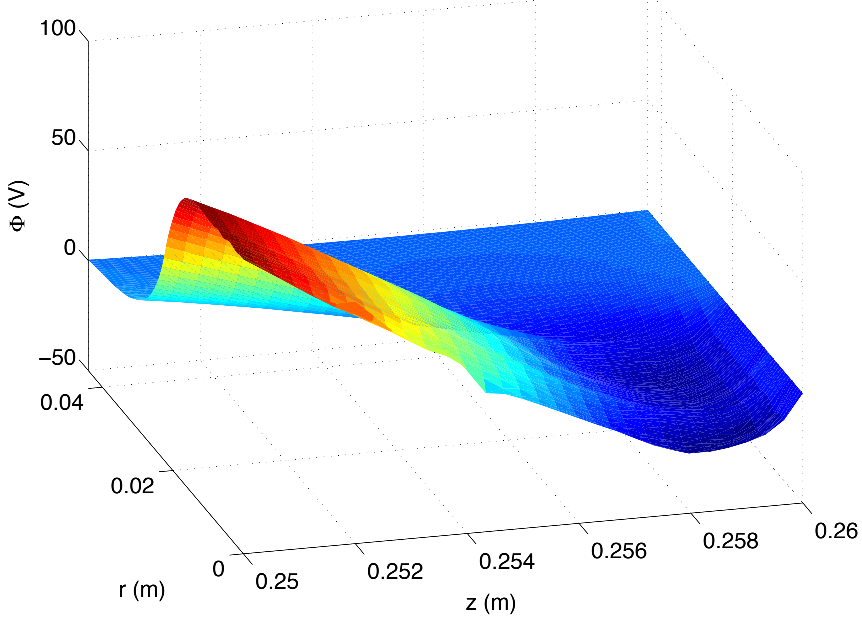
[1] Verboncoeur et al., *Comp. Phys. Comm.* **87**, 199 (1995)

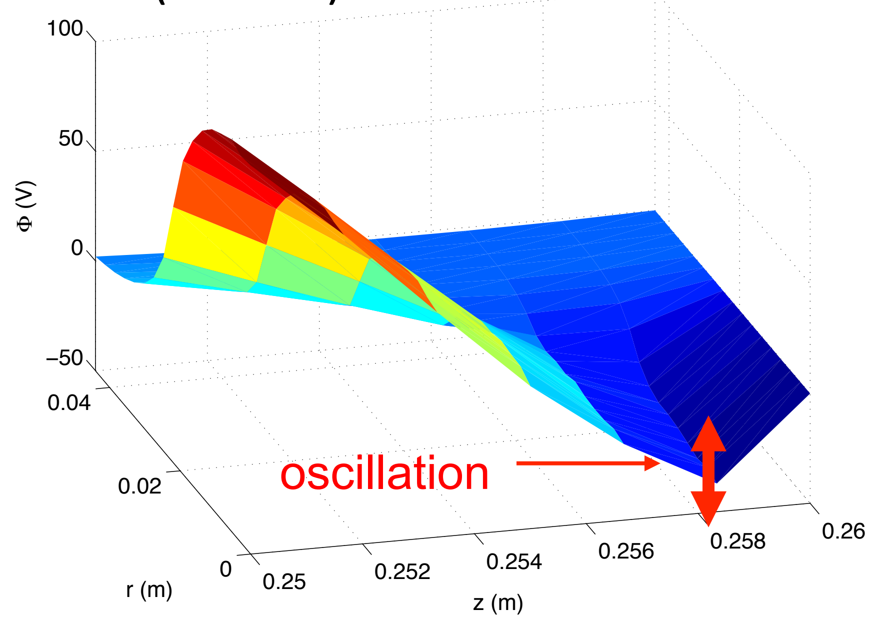
Spurious oscillations observed when VC is not resolved

Potential in vicinity of virtual cathode region (t=2μs, Δt=0.2ns)

high resolution (200x780) $\begin{cases} \Delta r = 0.55\ \text{mm} \\ \Delta z = 1/3\ \text{mm} \end{cases}$

low resolution (40x156) $\begin{cases} \Delta r = 2.75\ \text{mm} \\ \Delta z = 5/3\ \text{mm} \end{cases}$





$$\Phi_{\min} = -24\ \text{V}$$

$$-70 \le \Phi_{\min} \le -25\ \text{V}$$

Mesh refinement very helpful for modeling of HCX magnetic section!